

# Cryogenic Selective Surfaces A Phase 2 NIAC Project

## Mid-Term Continuation Review

Robert Youngquist, Mark Nurge, and Tracy Gibson of KSC, NASA  
Wesley Johnson of GRC, NASA

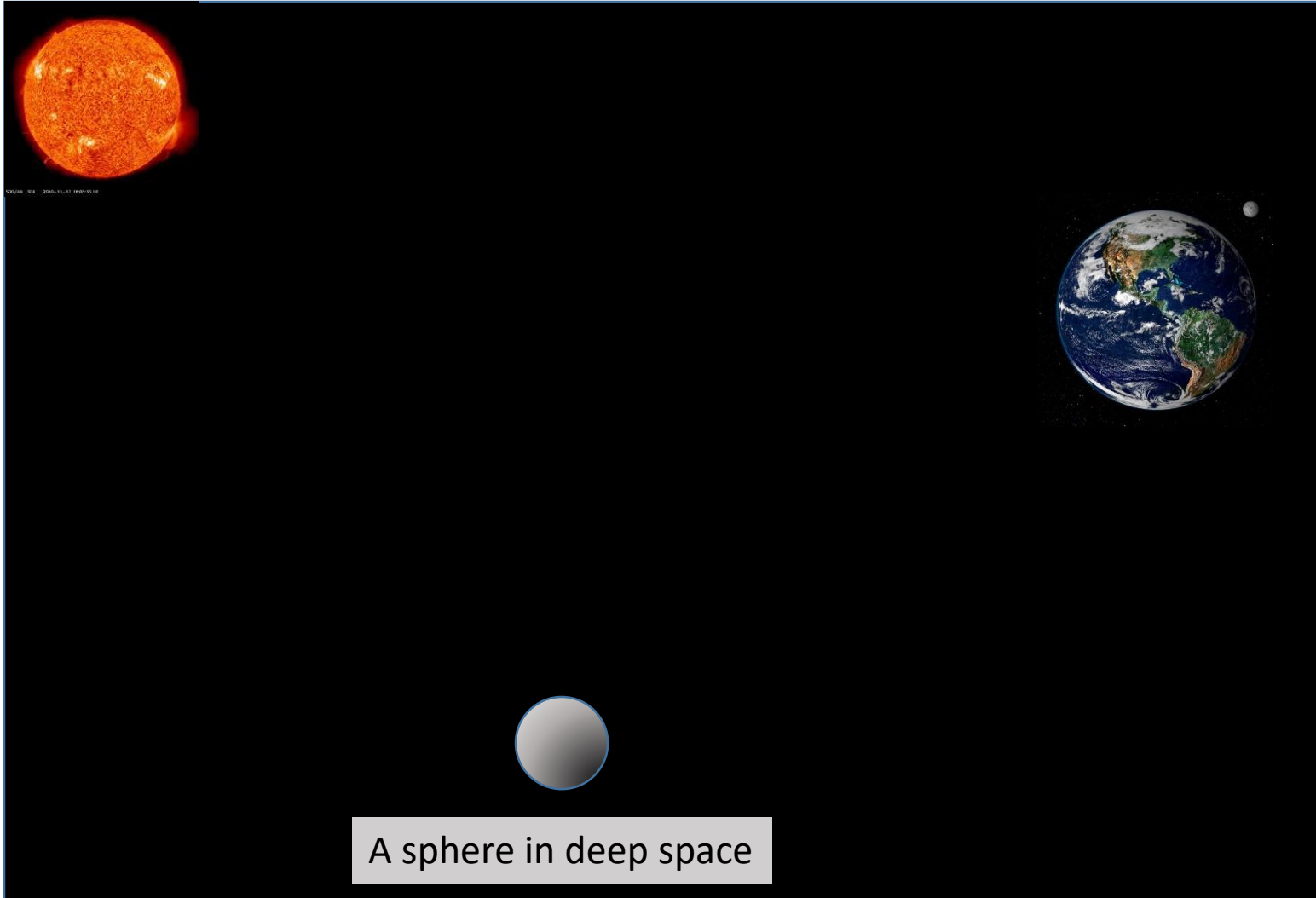
# Cryogenic Selective Surfaces



## Presentation Outline:

9:00-9:15	Introductions
9:15-9:40	Background, state-of-the-art, and introduction to the concept.
9:40-10:00	The path from powder to rigid coatings
Brief break	
10:10-10:30	Deep space simulated testing—cryogenic testing
10:30-10:50	LOX in space-mission to Mars, storage on the Moon, low earth orbit storage
Brief Break	
11:00-11:15	Other applications of this new coating
11:15-11:25	Plans for the second year
11:25-11:35	Plans for beyond NIAC, Game Changing, eCryo, and Launch Services Program
11:35-11:45	Finances
11:45-12:00	Open Discussion

# Cryogenic Selective Surfaces

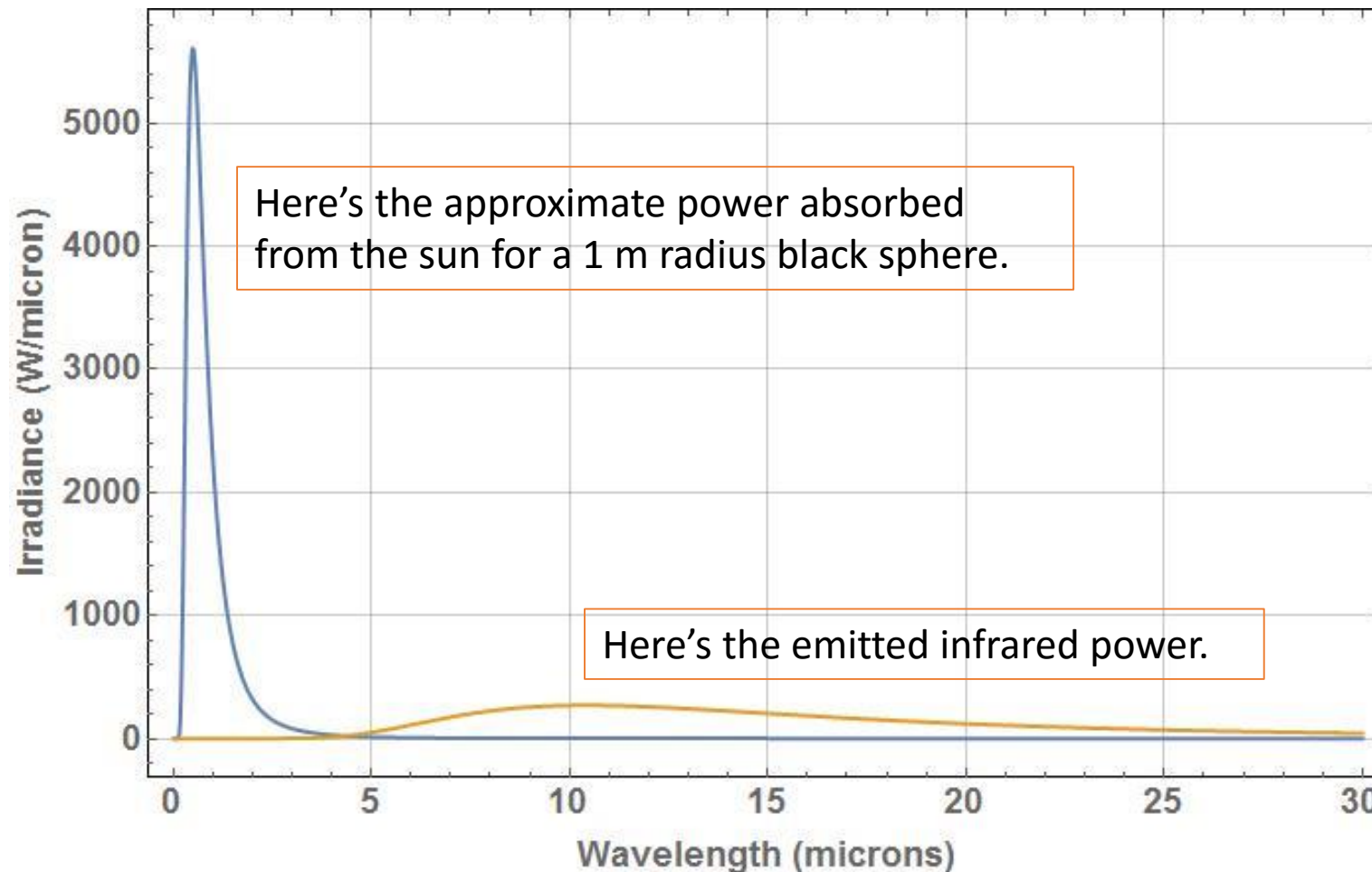


If we place a sphere in deep space at 1 AU from the sun, what will its temperature be, assuming it absorbs radiation from the sun and emits infrared radiation in all directions?

Our goal is to find a way to make this sphere as cold as possible so that we can potentially store liquid oxygen or operate superconductors.

# Cryogenic Selective Surfaces

If the sphere is black, or grey, it will reach a temperature of about 278 K, 41 °F, where the solar power absorbed equals the infrared power emitted. This is slightly lower than the Earth's temperature because of the absence of greenhouse effects.



The important concept here is that the Sun's power is mostly in the visible, while the emitted power is mostly in the infrared.

For this talk:

Ultraviolet is 0.1 to 0.4 microns  
Visible is 0.4 to 0.7 microns  
Near IR is 0.7 to 1.5 microns  
Mid-IR 1.5 microns to 7 microns  
Far-IR is 7 microns to 14 microns  
Long Wave is beyond 14 microns.

# Cryogenic Selective Surfaces

In order to get cold you need to reflect the Sun's radiation while allowing the emission of long wave radiation.

This is well known. The document to the right lists nearly 200 films, material, paints, and coatings providing their solar absorptance and thermal emittance so that equilibrium temperatures can be calculated for spacecraft.

Some of the best are white paints that reflect 94% of the Sun's power and still emit as an 88% blackbody in the infrared.

AZ Technology sells a white paint with 9% visible absorption and 91 % IR emission.

## NASA Reference Publication 1121

April 1984

## Solar Absorptance and Thermal Emittance of Some Common Spacecraft Thermal-Control Coatings

John H. Henninger

*Index*  
*entered in  
manual  
sep 1984*

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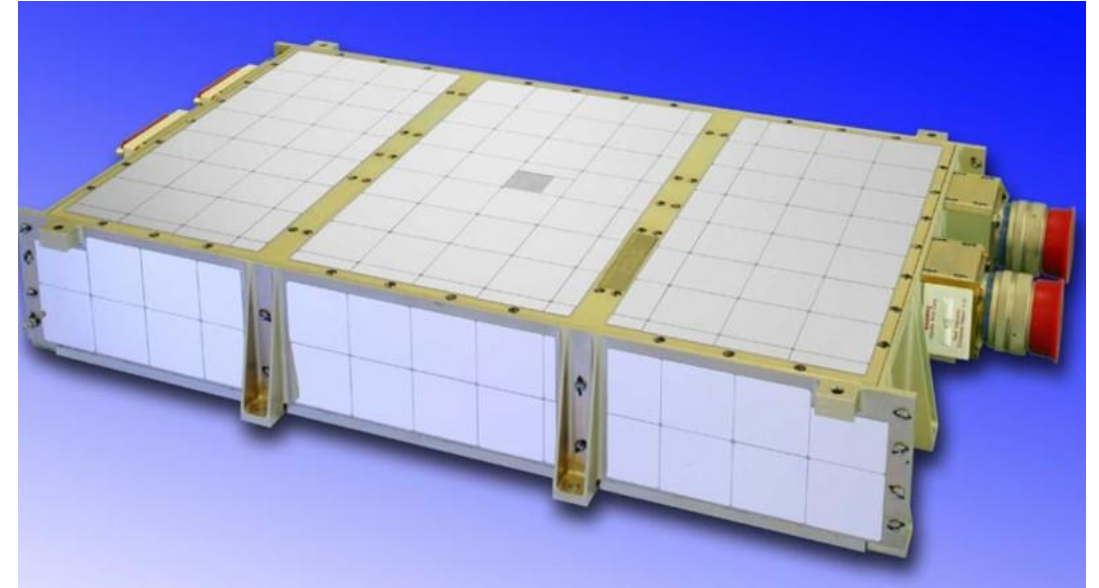
# Cryogenic Selective Surfaces

Another option is to coat a transparent material with silver or aluminum, i.e. a second surface mirror, where the transparent material becomes black in the infrared.

The best second surface mirror is composed of quartz on silver. One version of this from Qioptiq (shown to the right).

Their best “optical solar reflector” absorbs only 6% of the Sun’s power and radiates with 83% efficiency in the infrared.

This is the current state-of-the-art.

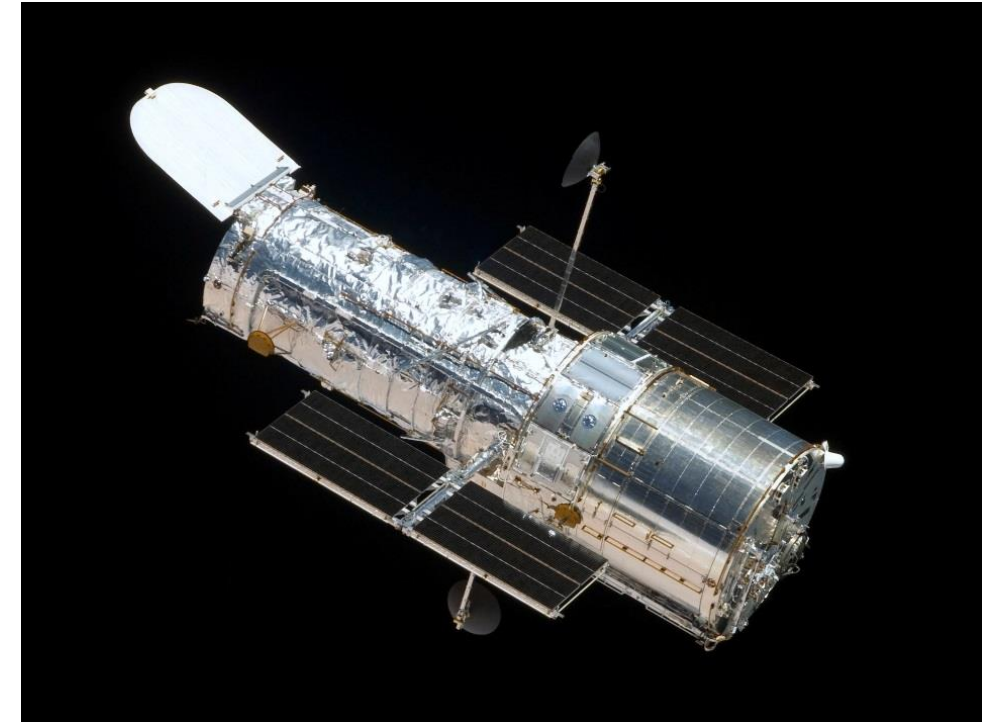
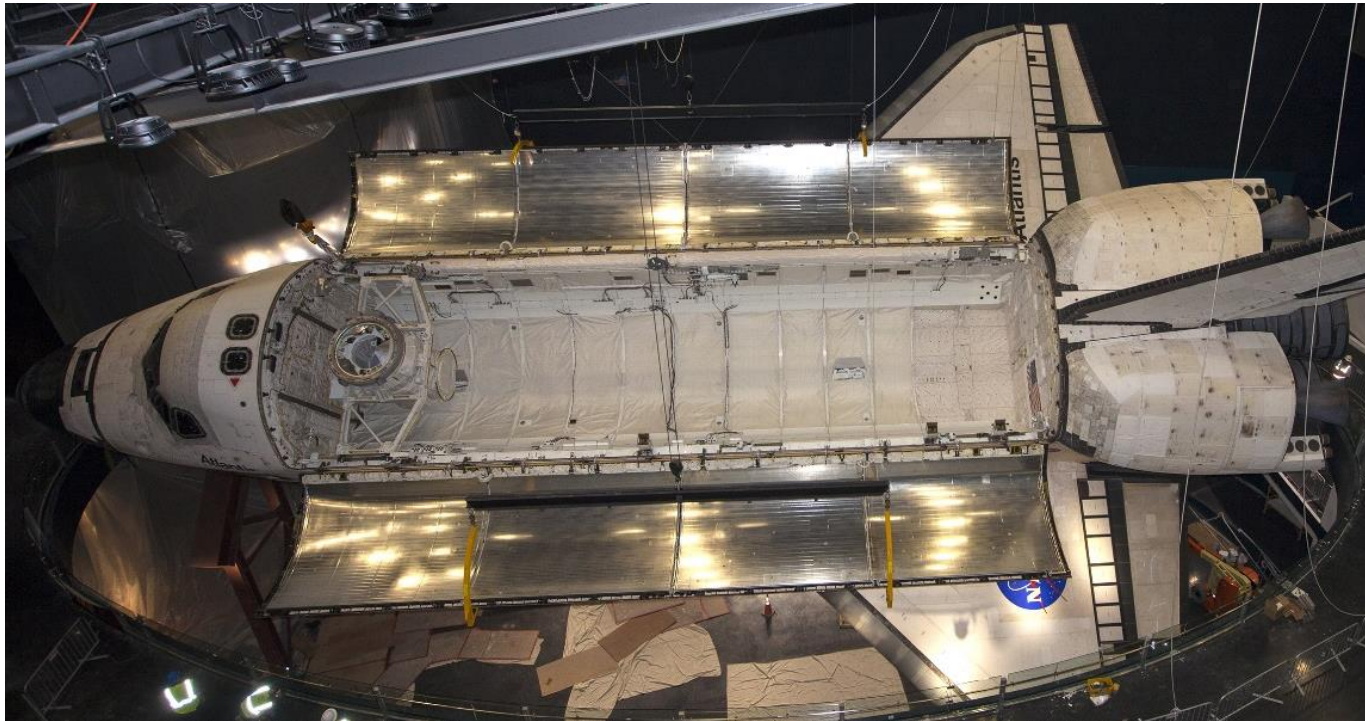


An object cover with Qioptiq’s solar reflector.



# Cryogenic Selective Surfaces

Companies such as Sheldahl sell second surface mirror sheets composed of silver on FEP (type of Teflon). These flexible reflectors/radiators have been used to remove waste heat from the Shuttle and the Hubble telescope while in the presence of the Sun.



These materials absorb about 9-10% of the Sun's power and can emit with 75-80% efficiency in the infrared.

# Cryogenic Selective Surfaces



But none of these will reach cryogenic temperatures.

A black coated LOX tank at 90K emits 3.7 Watts/square meter of surface area.

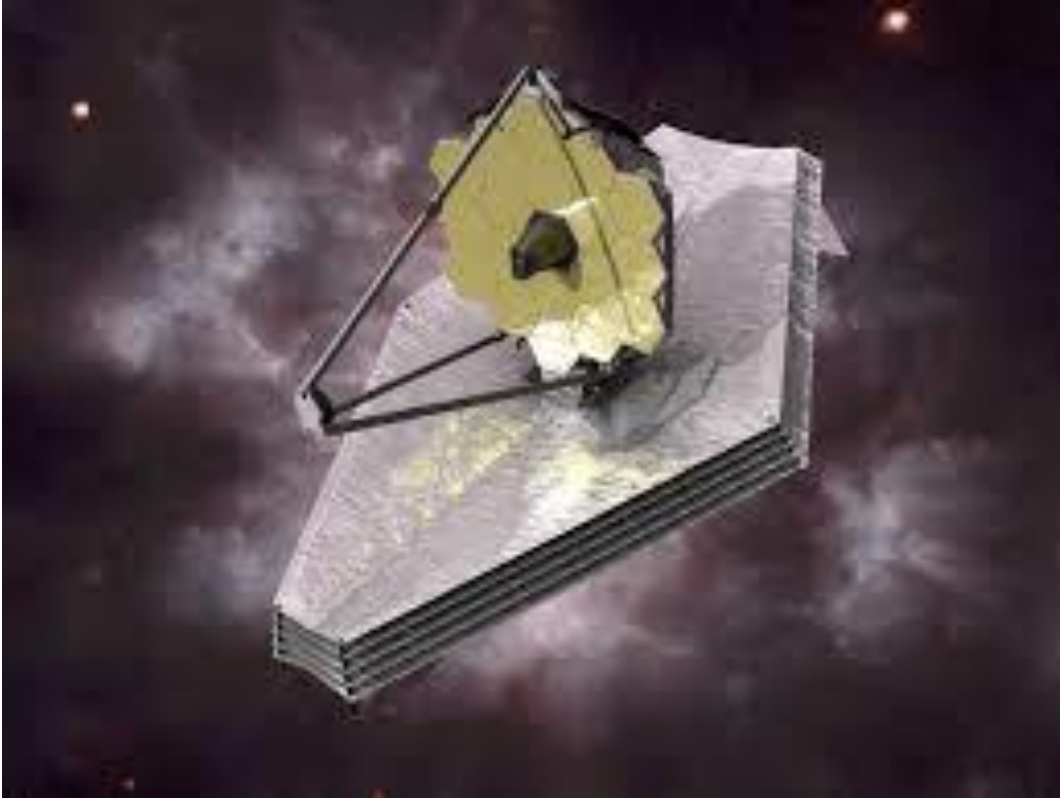
The Sun's total irradiance is 1366 Watts/square meter.

So with a 100% emitter in the infrared we can only absorb about 0.01 of the Sun's power, a factor of 6 times lower than the best currently available surface (the Qioptiq solar reflector).

We need a new approach.



# Cryogenic Selective Surfaces



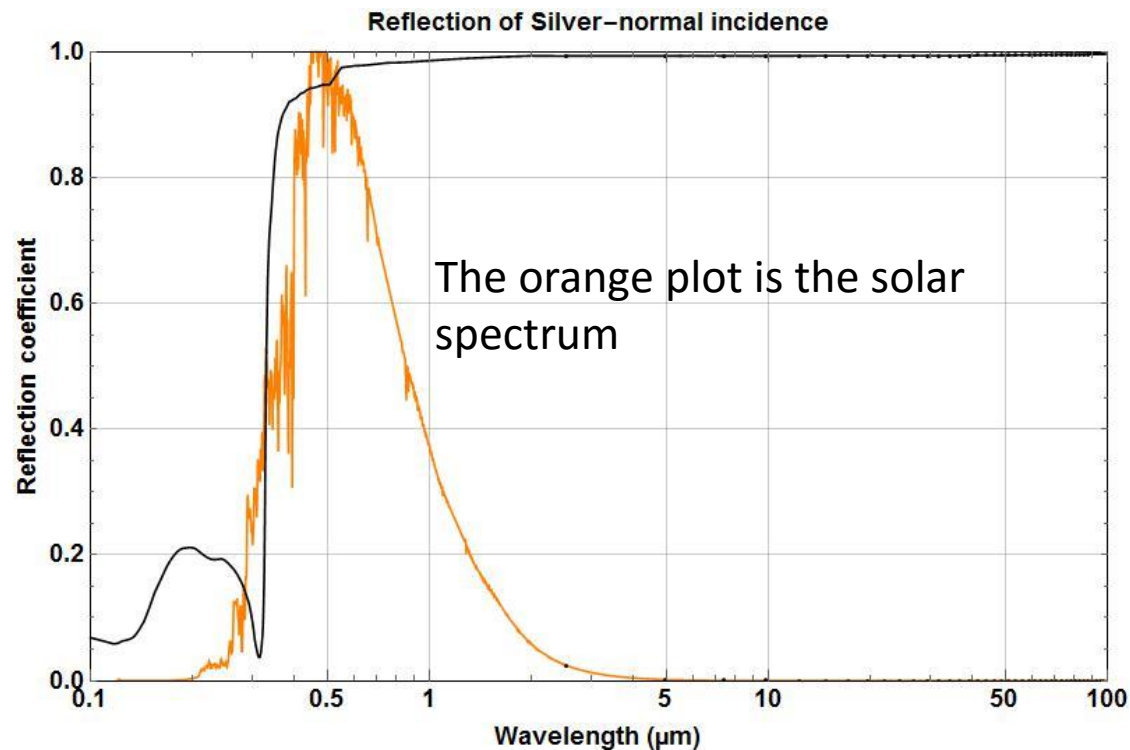
For completeness; A multi-layer shield can block radiation if the spacecraft can be oriented relative to emitters.

The James Webb Telescope is an example of this as seen in the photo. It will be at a Lagrange Point where the direction to the Earth and Sun are fixed. For most missions a shield is not an option, but the approach is worth mentioning.

Note that placing a shield completely around a spacecraft just shifts the emission/absorption problem to the shield.<sub>9</sub>

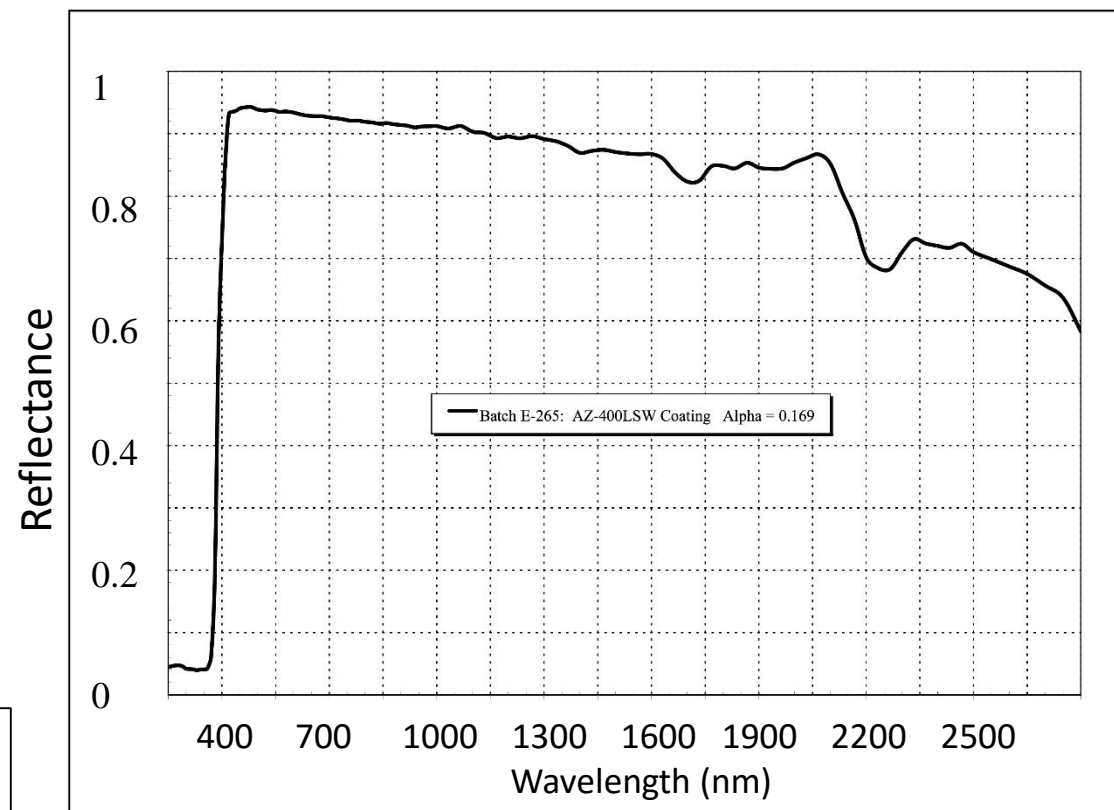
# Cryogenic Selective Surfaces

So what limits the current state-of-the-art?



The problem is that the metals used in second surface mirrors, as well as most white paints, absorb substantial ultraviolet radiation. We cannot get cold with either of these.

Total Hemispherical Spectral Reflectance for AZ-400-LSW  
White Silicone Semi-flat Marker Coating



# Cryogenic Selective Surfaces

The optics community had a similar problem and solved it in 1968 by recognizing that powders composed of transparent materials scatter light and will reflect nearly all of the light that hits them within their transparency window.

## Optical Sphere Paint and a Working Standard of Reflectance

F. Grum and G. W. Luckey

Specially prepared barium sulfate powders and coatings of these powders with polyvinyl alcohol have been used as working standards of reflectance and for coating integrating spheres. These materials are satisfactory for use in the wavelength range 0.20–2.00  $\mu$ . Since the refractive index of barium sulfate is rather low, it is necessary to use fairly thick layers in order to obtain good results. The absolute value of luminous reflectance of the barium sulfate powder, described in this paper, is  $0.995 \pm 0.001$ , and that of the paint, when properly applied, is  $0.992 \pm 0.001$ . The spectral reflectance of this material is higher than that of magnesium oxide, particularly in the uv region of the spectrum. By using barium sulfate as reference standard and as a coating on the integrating spheres of spectrophotometers, it is now possible to measure spectral reflectance reliably in the uv region to 200 nm. Because the reflectance of barium sulfate paint is significantly greater than that of magnesium oxide in the shortwave region, there is a corresponding gain in instrument sensitivity when barium sulfate is used as a sphere coating and as a comparison material.



Spectralon: A surface used in the optics community as a white standard.

# Cryogenic Selective Surfaces



Snow, clouds, and powdered sugar are all white because water and sugar do not absorb visible light and in particle form they then scatter light. Note that the underside of the clouds are dark, indicating the Sun's energy has been reflected, not transmitted.

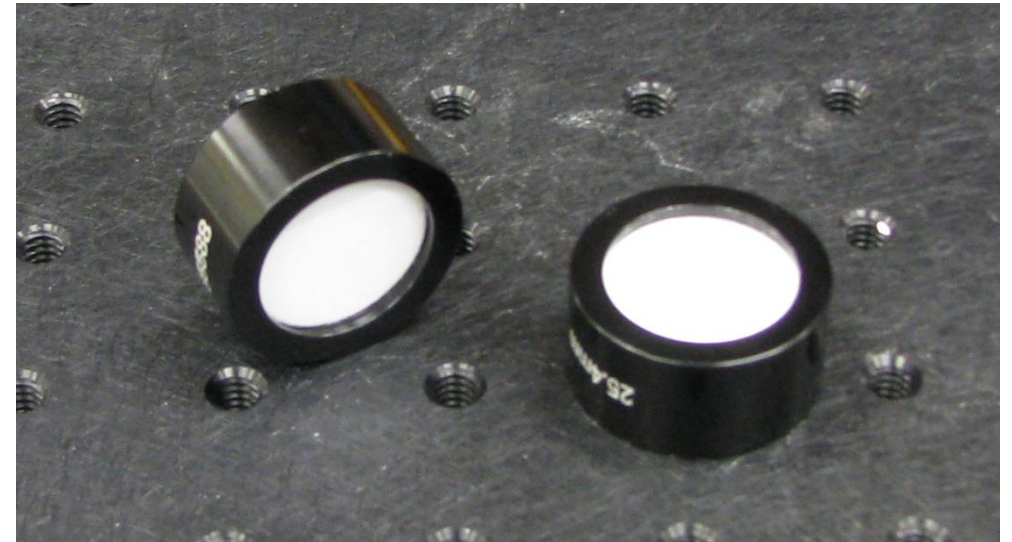


# Cryogenic Selective Surfaces

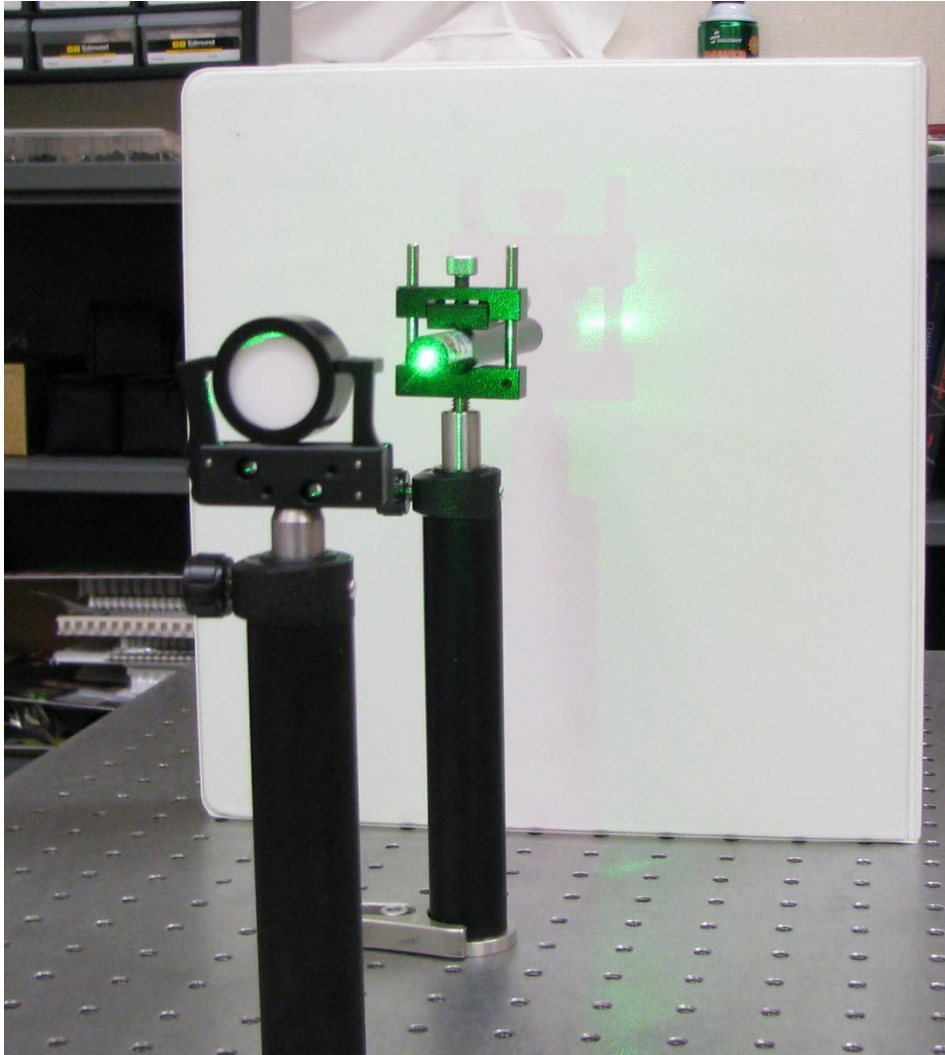


Titanium Dioxide Powder-0.25 micron transparent particles used to make things white, including paint, cottage cheese, skim milk, toothpaste, some cheeses and ice creams, etc.

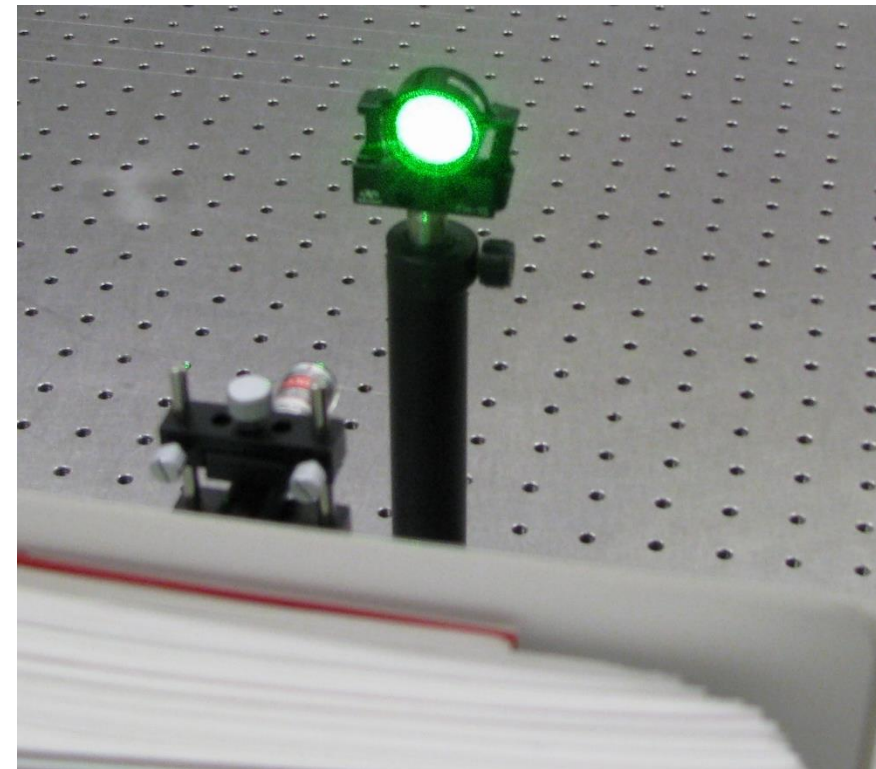
Before continuing, let's do a quick test. The paint industry uses TiO<sub>2</sub> particles to scatter visible radiation, allowing "items" to look white. Let's put 6 mm of TiO<sub>2</sub> powder into a 1 inch diameter cell and hold it in place with two glass windows, as shown below.



# Cryogenic Selective Surfaces



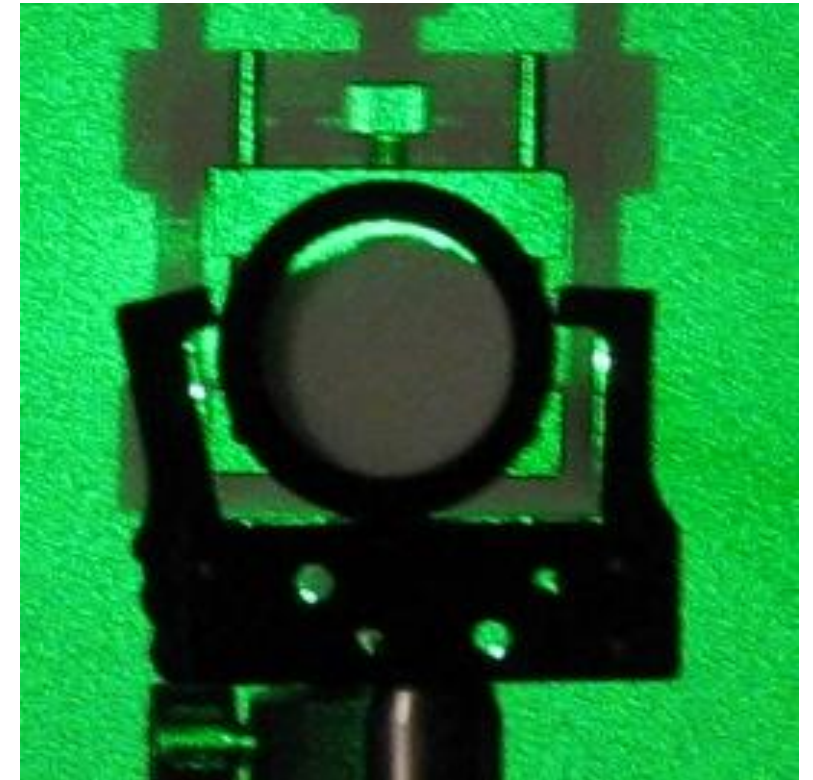
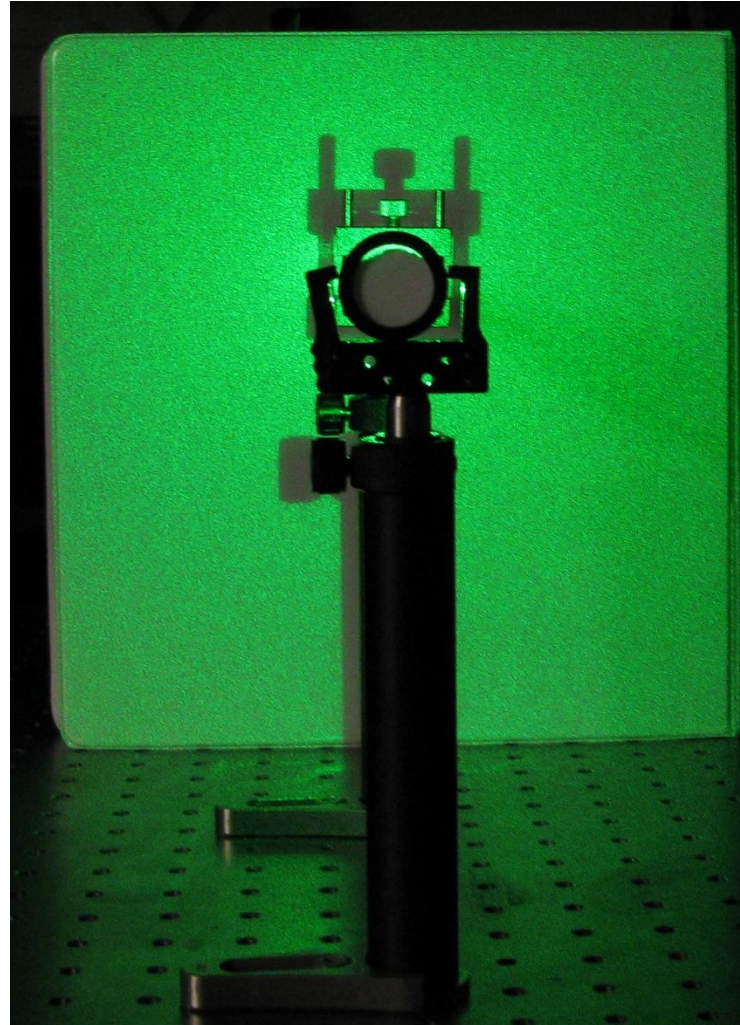
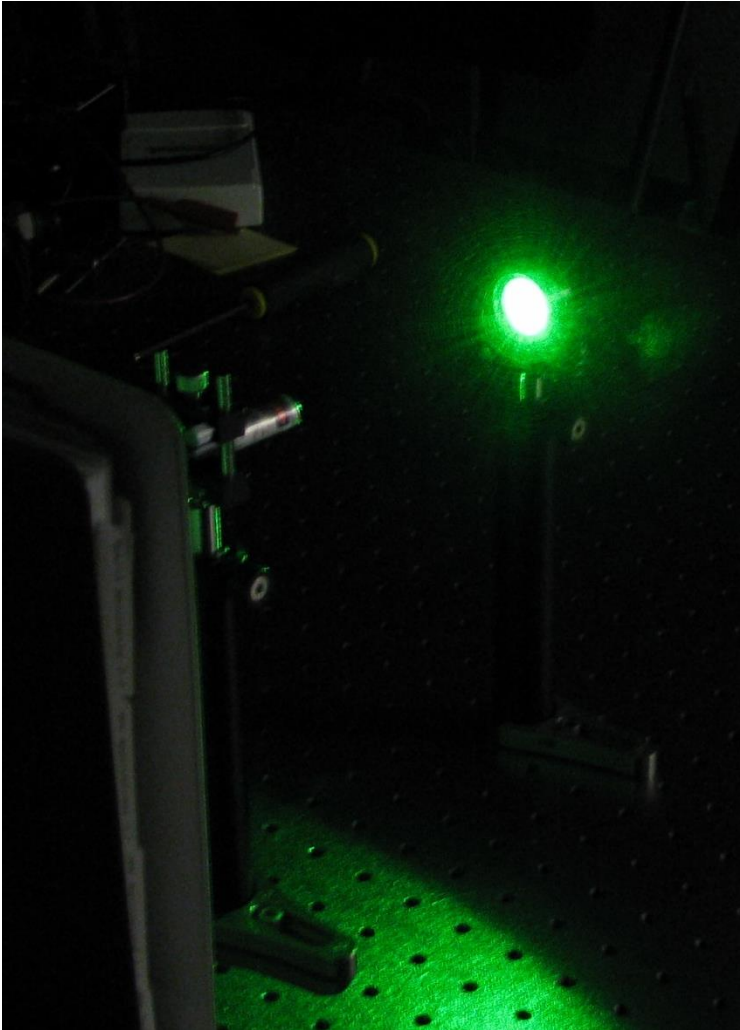
If we launch a 5 mW green laser at this layer essentially no light gets through, most being scattered backward.





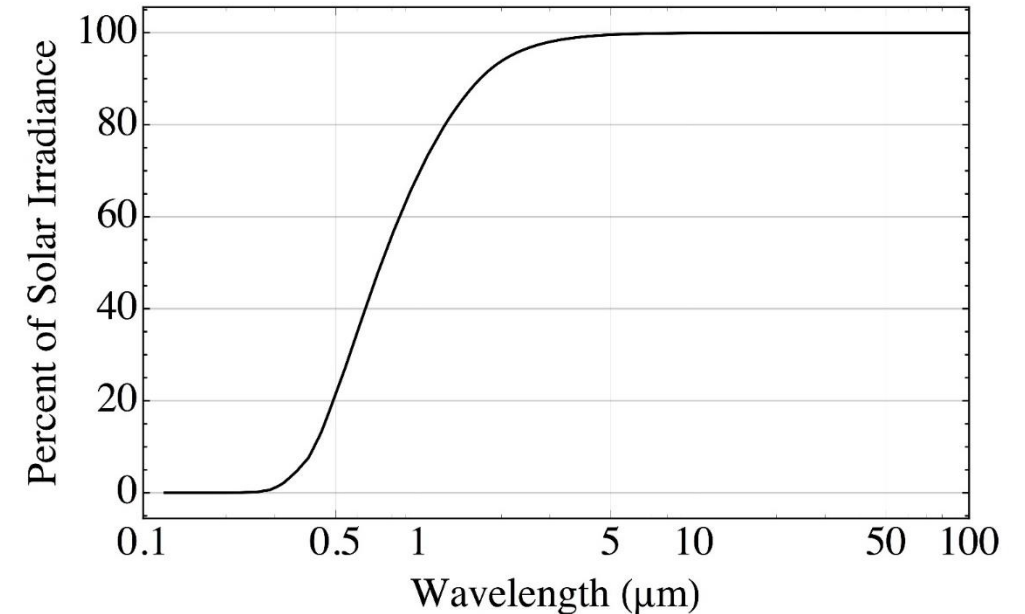
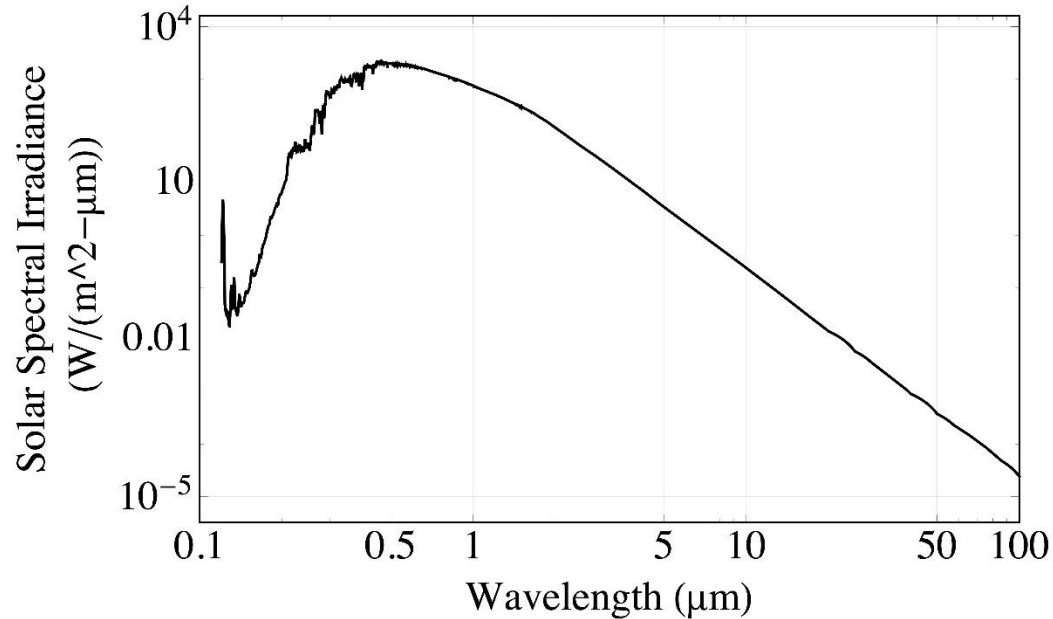
# Cryogenic Selective Surfaces

This is even more apparent if we turn out the lights.



Very high reflectivity with essentially no transmission.

# Cryogenic Selective Surfaces



But all of these powders absorb too much of the Sun's energy to be useful. We need materials that absorb very little of the Sun's power. Analysis of the Sun's spectrum shows that we need materials that are transparent from about 0.2 microns to roughly 7-8 microns or beyond.

# Cryogenic Selective Surfaces

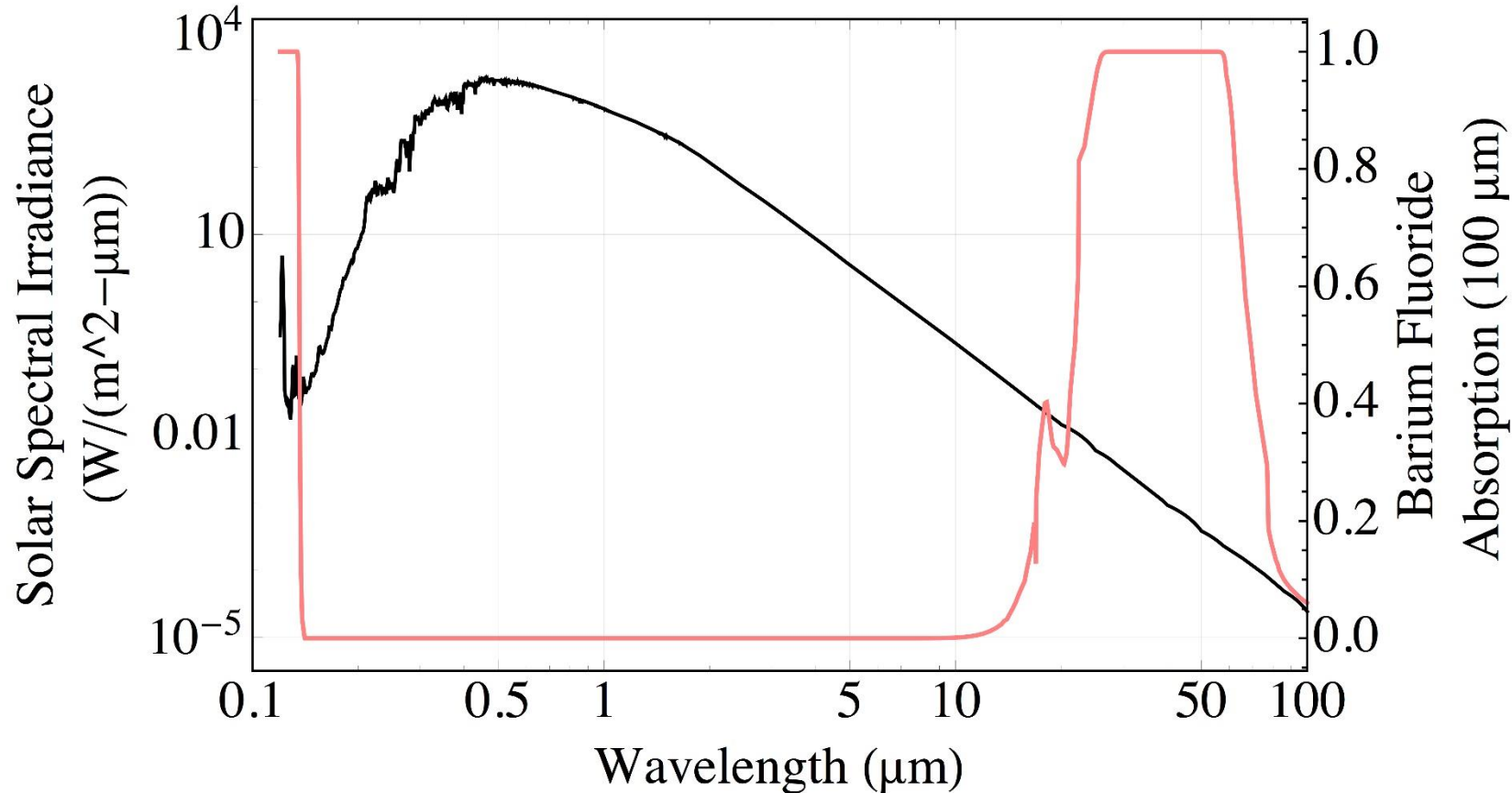
**Table 1. Possible Materials for the Cryogenic Thermal Control Coating**

Material	UV Transition ( $\mu\text{m}$ )	IR Transition ( $\mu\text{m}$ )	Comments
CaF <sub>2</sub>	0.12	8–9	Good available material.
MgF <sub>2</sub>	0.12	8	Good available material, but shorter IR absorption than CaF <sub>2</sub> and more expensive.
BaF <sub>2</sub>	0.14	12–14	Very good material. Rugged, available, wide UV-IR band.
SrF <sub>2</sub>	0.13	10	Properties between CaF <sub>2</sub> and BaF <sub>2</sub> . Not common.
NaCl	0.17–0.3	20	Might have UV absorption. Water solubility is an issue.
CsBr	0.20	30–40	More difficult to obtain. Some UV absorption. Very long wave IR transition.
NaF	0.14	10	Low index. Not common, but good transmission band.
KCl	0.18	18	Inexpensive. Good transmission band
KBr	0.21	20–30	Readily available, some UV absorption.

Fortunately there are several such materials and some are readily available and have well known optical parameters.

The best of these based on availability, water solubility, and overall performance is Barium Fluoride. It will be the basis of most of our work.

# Cryogenic Selective Surfaces

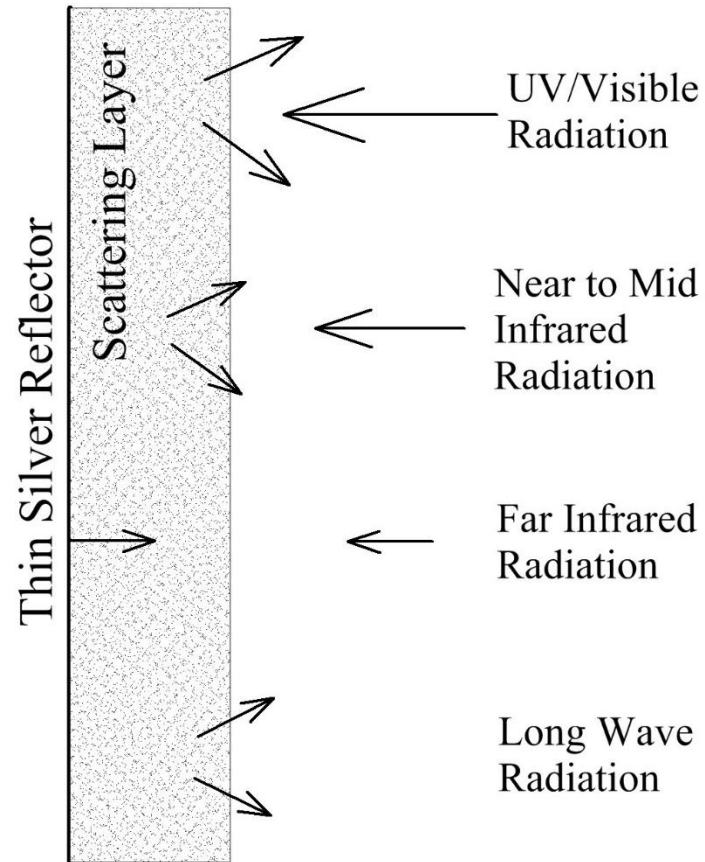


This plot shows the absorption of a 100 micron thick sheet of BaF<sub>2</sub> overlaid onto the Sun's spectral irradiance. It shows that BaF<sub>2</sub> absorbs very little of the Sun's energy and is a good choice for our new coating.



# Cryogenic Selective Surfaces

Our new coating is composed of a scattering layer followed by a silver layer. The scatterer handles the UV and visible reflectance and the silver reflects mid-long wave radiation.



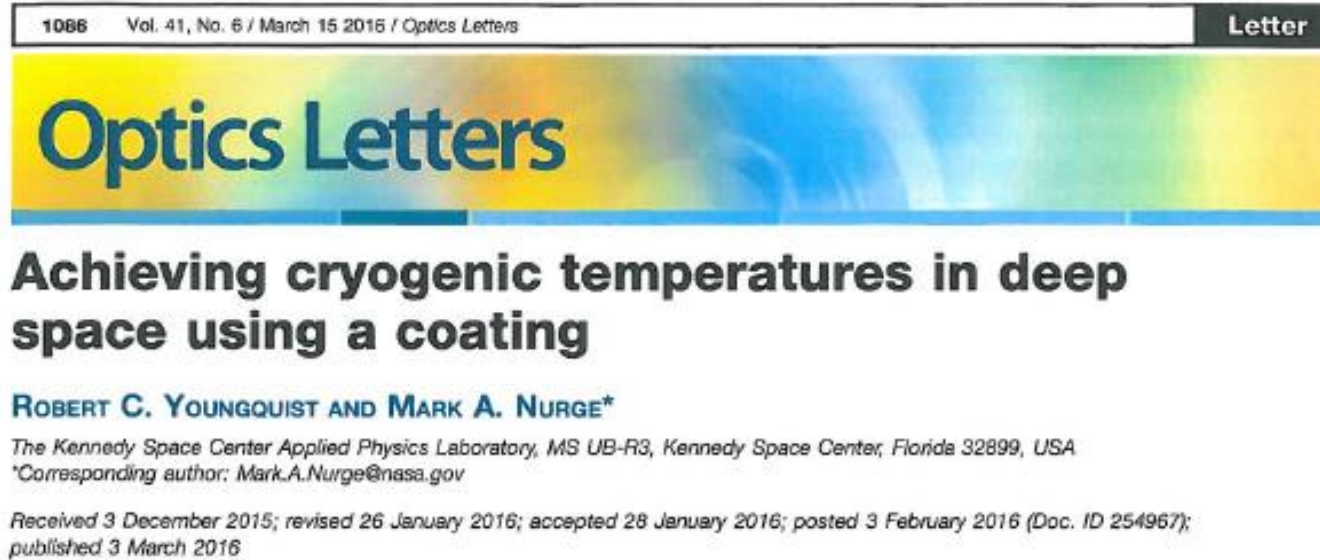
First, choose a material that absorbs essentially no radiation from 0.2 microns to the mid or far infrared range, e.g.  $\text{MgF}_2$ ,  $\text{CaF}_2$ ,  $\text{BaF}_2$ ,  $\text{KBr}$ ,  $\text{NaCl}$ , etc.

Second, grind this material into 200-300 nm diameter particles and make a 3-10 mm layer of this powder. This layer will scatter UV, visible, and near infrared light effectively, but not longer wave radiation.

Third, place this layer on a metallic reflector (e.g. silver) to reflect the longer wave radiation that gets through the particle layer.

The coating will emit long wave radiation beyond its transparency cut-off.

# Cryogenic Selective Surfaces



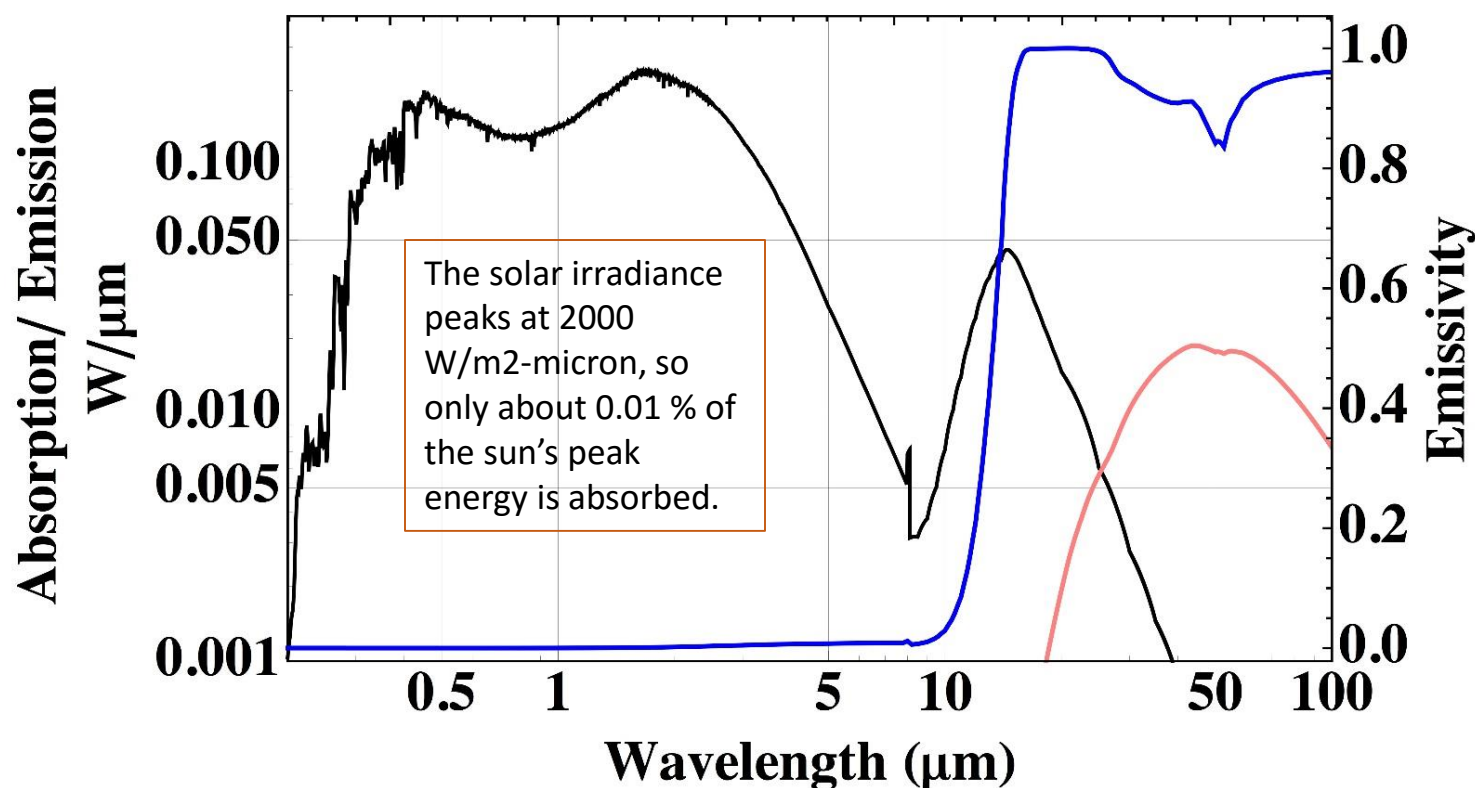
We developed a detailed model of the performance of this coating. We don't have time to go through that today, but it is documented in our NIAC Phase 1 final report and in a refereed journal publication in Optics Letters.



# Cryogenic Selective Surfaces

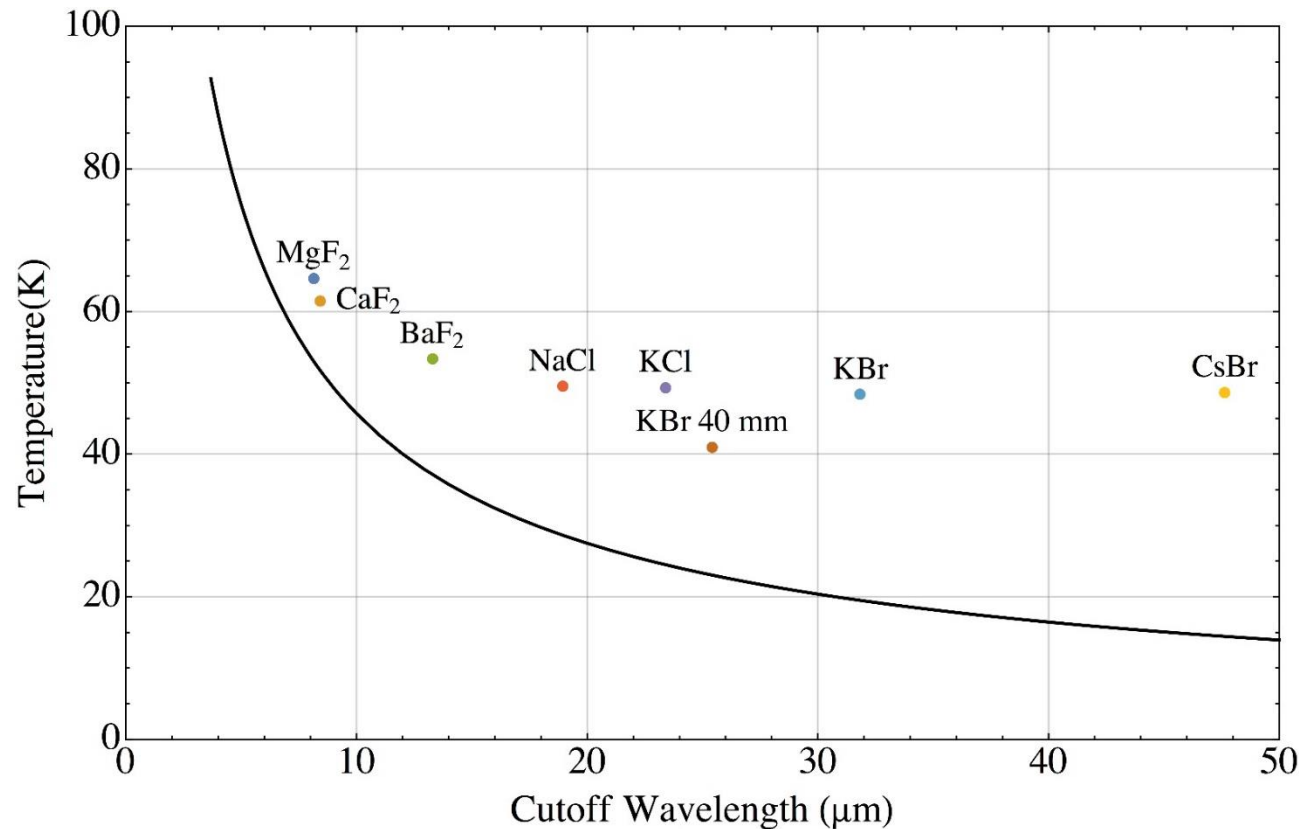
Here is a sample output from our model.

The plots below show the solar absorbed spectrum, the emitted power spectrum, and the emissivity for a 5 mm thick layer of BaF<sub>2</sub> on silver on a 1 m square flat plate facing the sun, coated on both sides.



A 1 m radius sphere would only absorb about 3.5 Watts of the 4300 Watts of solar power hitting it and would reach a predicted temperature of about **53 K !!**

# Cryogenic Selective Surfaces



We modeled 5 mm coatings on silver on our 1 m radius sphere for seven materials used as broadband spectroscopy windows.

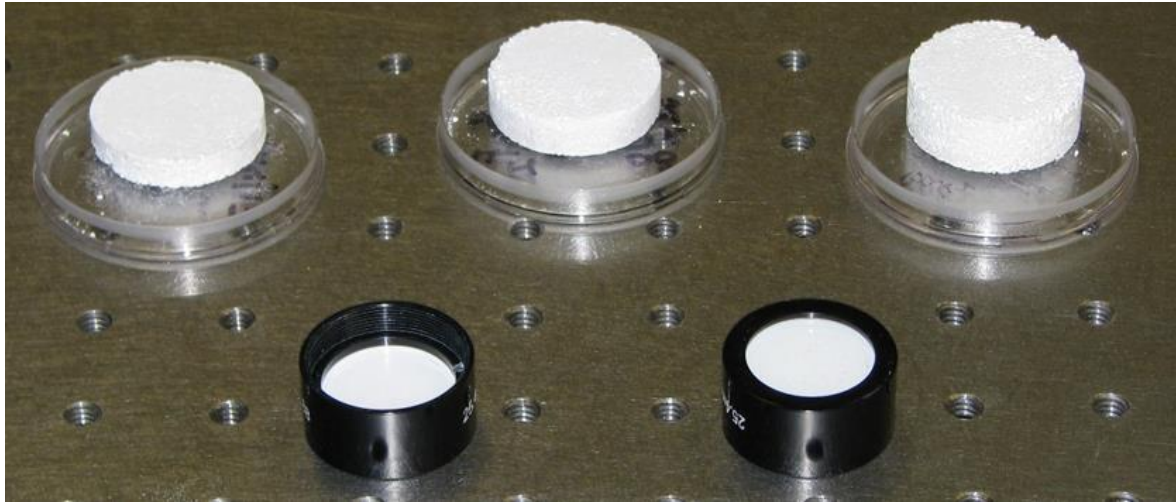
The line corresponds to an ideal material that reflects perfectly below the wavelength shown and is black above it. Hibbard, in 1961, first predicted this level of performance. So the line represents the theoretical best that can be reached.

Repeating—in 1961 it was known that cryogenic temperatures could be reached with an ideal coating. In 1968 the optics community found nearly ideal coatings. But it wasn't until 2015 that these two results were rediscovered and their potential impact realized.

# Cryogenic Selective Surfaces

But are our models any good?

The basic concept is straightforward and can be checked through simple back-of-the-envelope calculations. But we'd like to predict the actual performance of a given sample.



Sample	Measured Transmission	Predicted Transmission
3 mm BaF <sub>2</sub> Powder	1/17000	1/4300
6 mm BaF <sub>2</sub> Powder	1/300000	1/8600
6 mm thick Rigid BaF <sub>2</sub>	1/3000	1/4300
8 mm thick Rigid BaF <sub>2</sub>	1/10000	1/5700
11 mm thick Rigid BaF <sub>2</sub>	1/30000	1/7900

Here are five BaF<sub>2</sub> samples, two are powders and three are rigid samples. We predicted the transmission of visible light through these and then measured it. Note that in most of the cases the measured transmission is lower than the prediction, indicating that our model is conservative.

# Cryogenic Selective Surfaces



Testing has shown that our models, while capturing most of the physics, are only approximate. However, we have only put minor effort during the Phase 2 into improving the models because the Phase 2 proposal review stated:

**“The review panel would like the investigators to rework the plan to put a great emphasis on manufacturing and testing and less emphasis on modeling and analysis.”**

It also stated that **converting ultra-fine powder into a rigid structure would be “extremely difficult” and concerns were raised about material strength, thermal expansion, adhesion, etc.**

So let’s discuss our progress in this area over the last year.

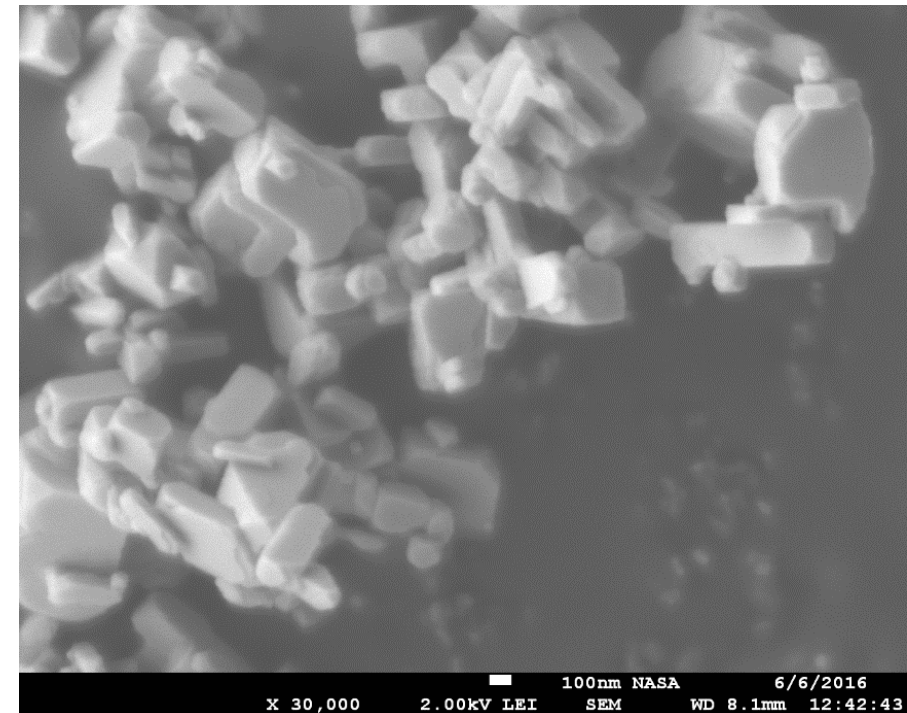
break point if needed

# Cryogenic Selective Surfaces

We considered several possible approaches to creating a rigid coating, but sintering was considered the most promising.



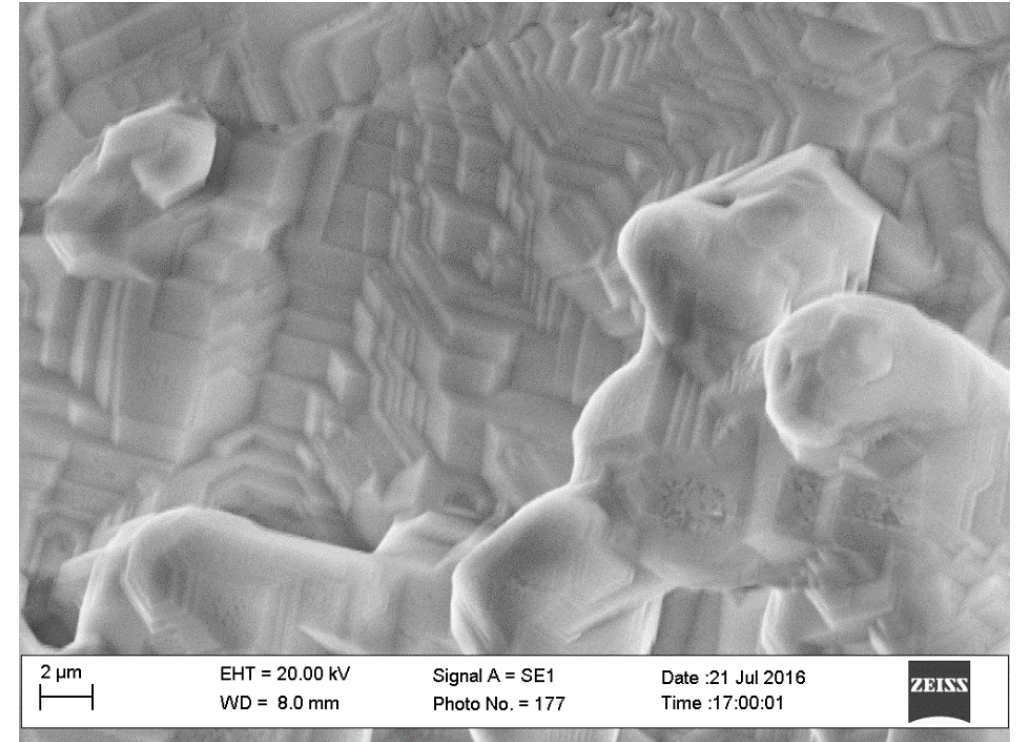
Here is BaF<sub>2</sub> powder placed on a 25 mm diam. 3 mm thick BaF<sub>2</sub> window.



The SEM shows particles about 200-300 nm in size (this is a perfect size)!



# Cryogenic Selective Surfaces

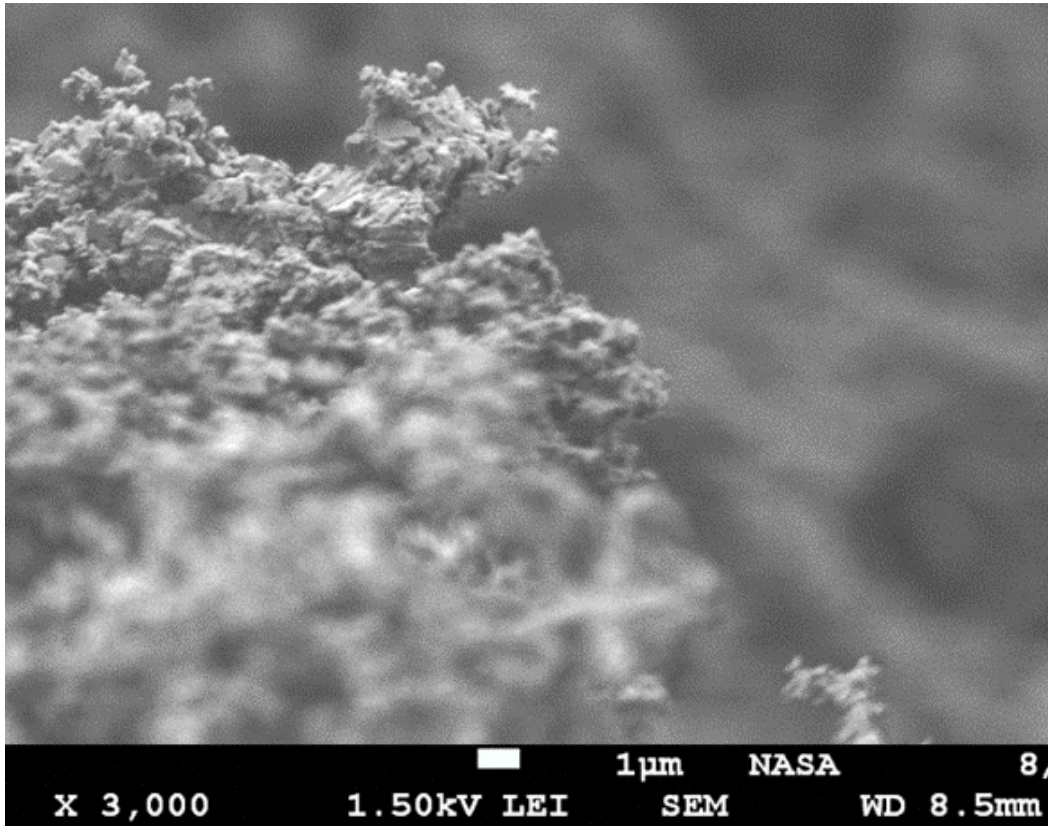


If we place the BaF2 powder in an oven the powder sinters and sticks to the BaF2 window.

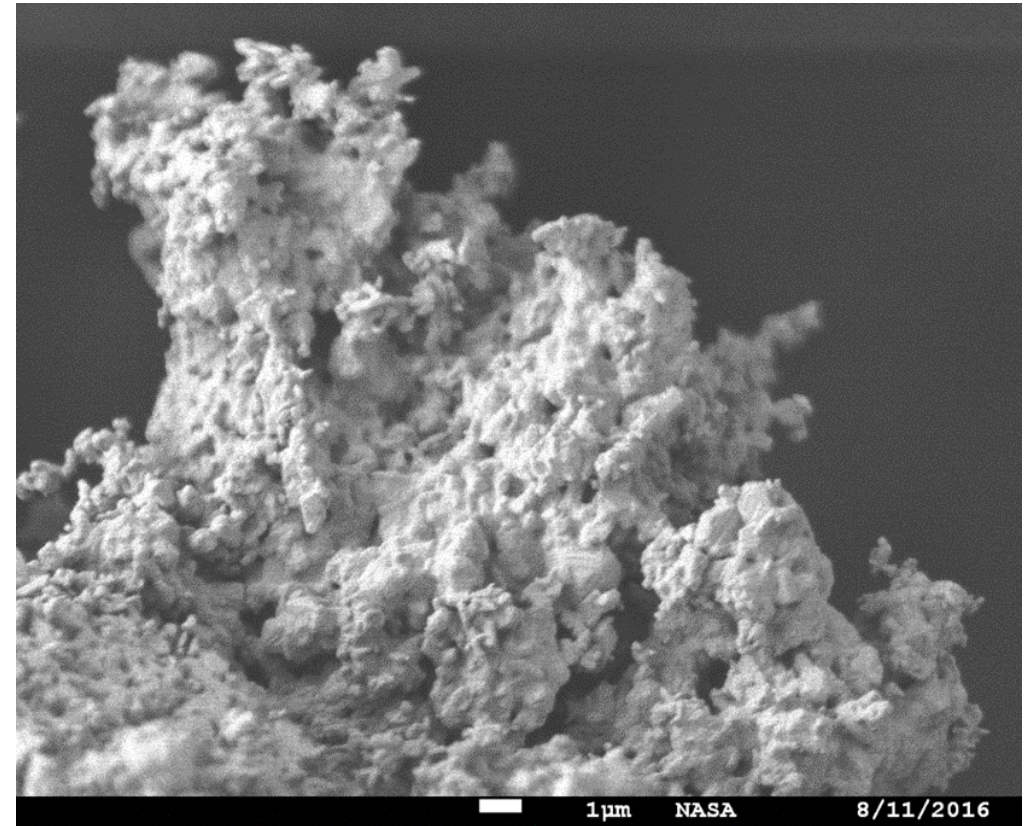
Our first try caused the particles to melt. We'd heated too long or too hot.



# Cryogenic Selective Surfaces



A better try—note that the small particle structure is still apparent.



A third try that went a little too far and started melting the particles again.

# Cryogenic Selective Surfaces



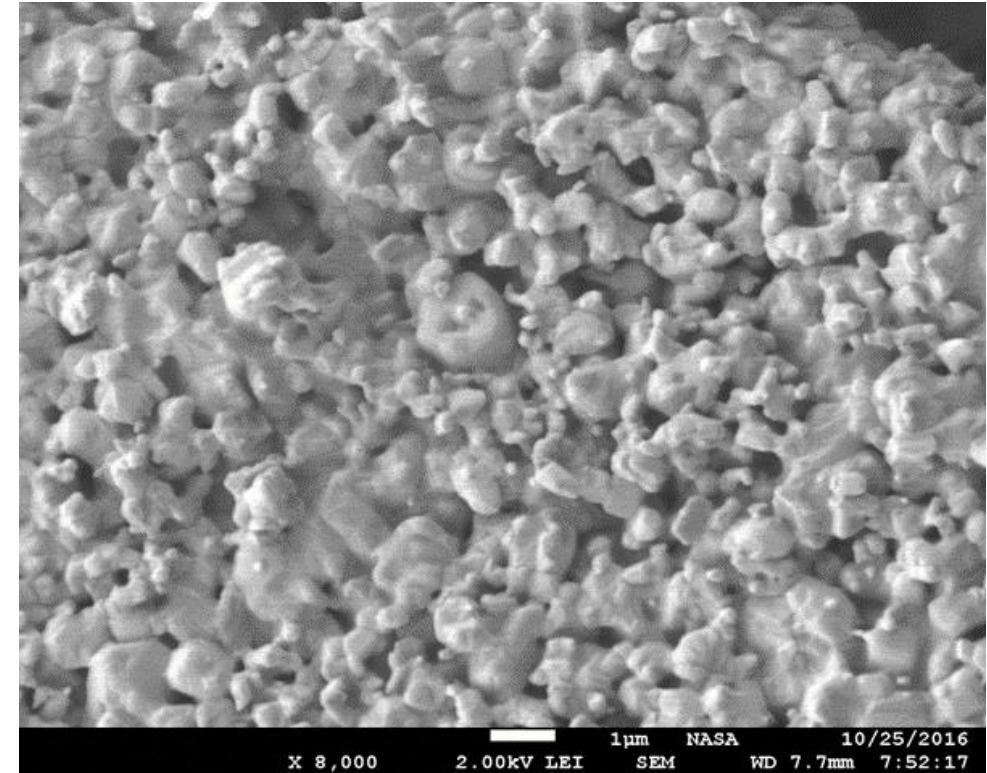
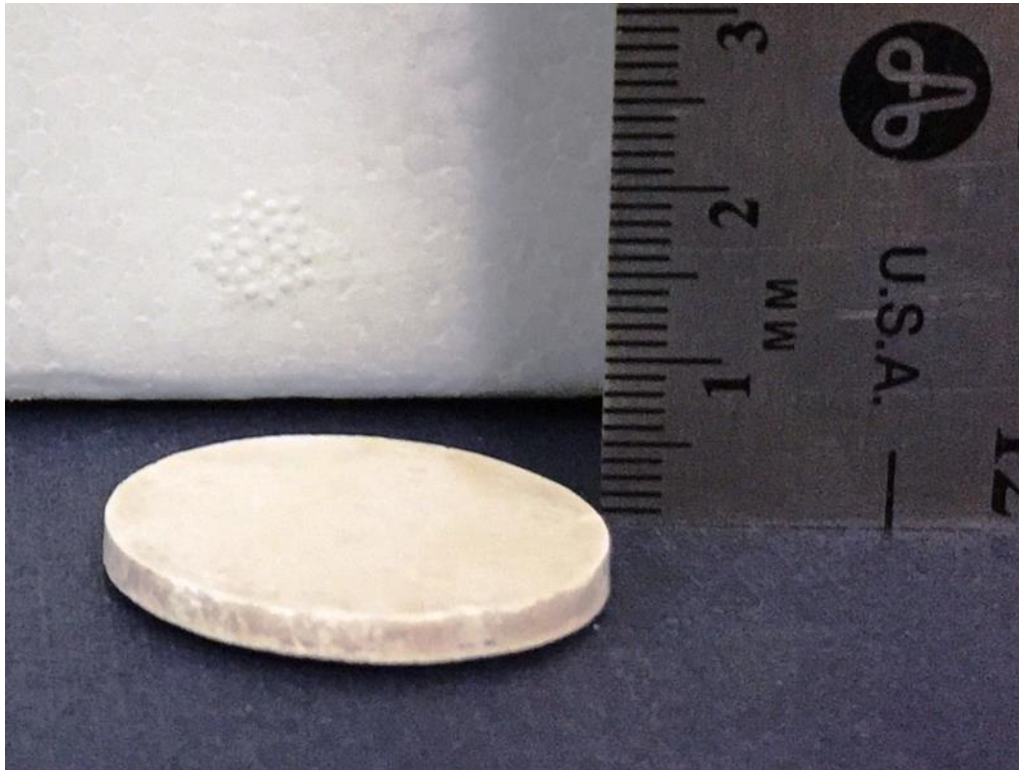
As of Sept. 2016, this was our best rigid sample.

We had found the best sintering conditions for loose powder, but now needed to create proper samples.

This would require making pastes, molds, and applying pressure.

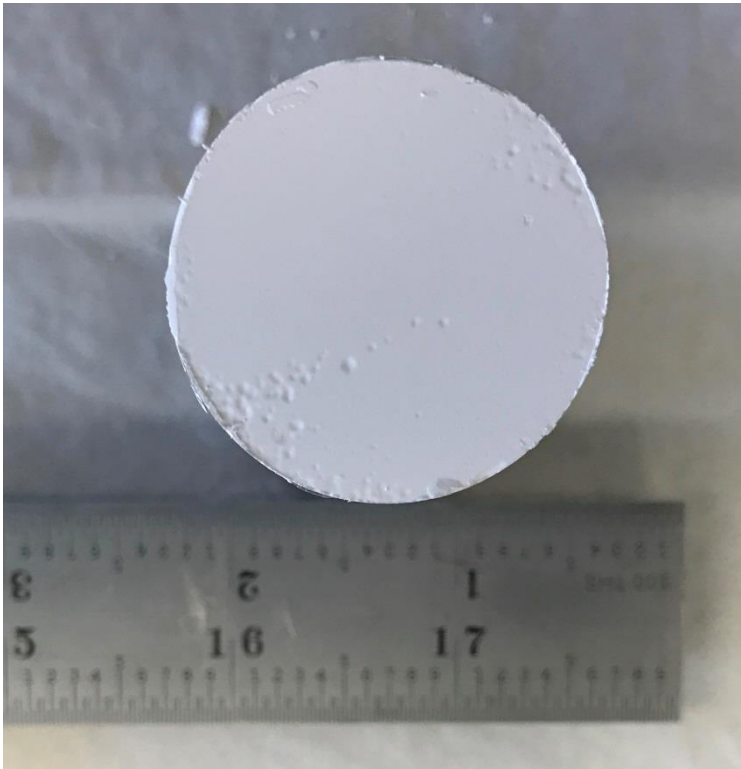


# Cryogenic Selective Surfaces



In October 2016 we tried applying high force to a BaF<sub>2</sub> paste (1500 kg with 10% water) and then sintering. This yielded a nice mechanical sample, but there was contamination and the particles were so compressed that optical performance was reduced.

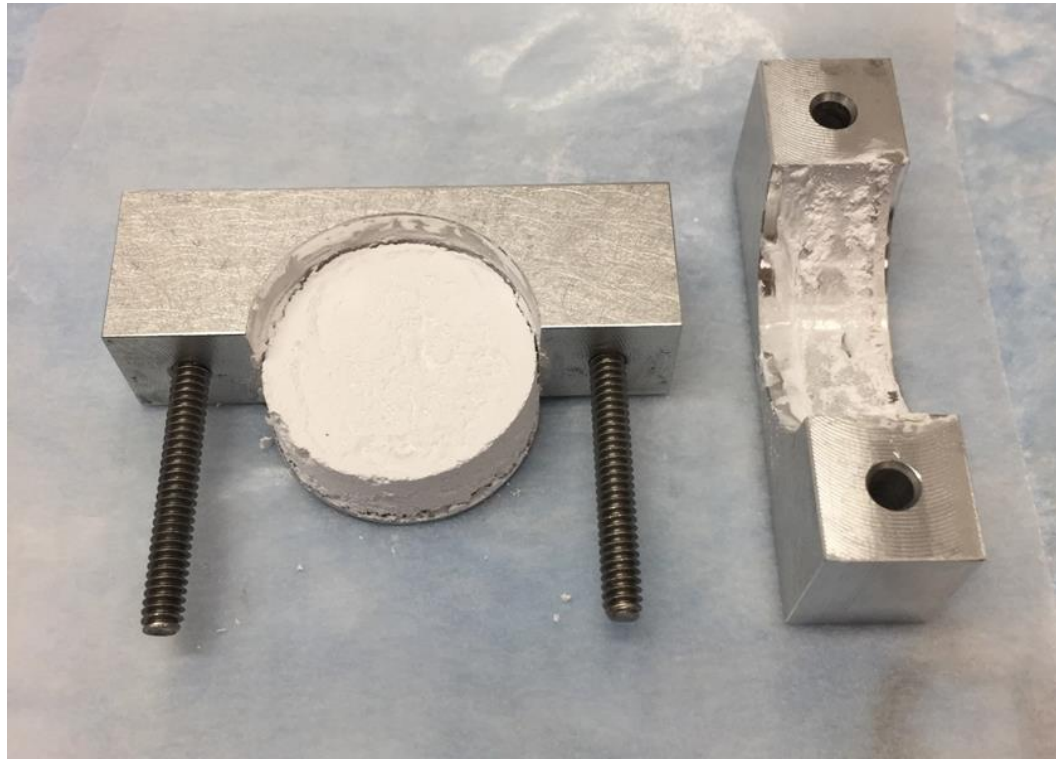
# Cryogenic Selective Surfaces



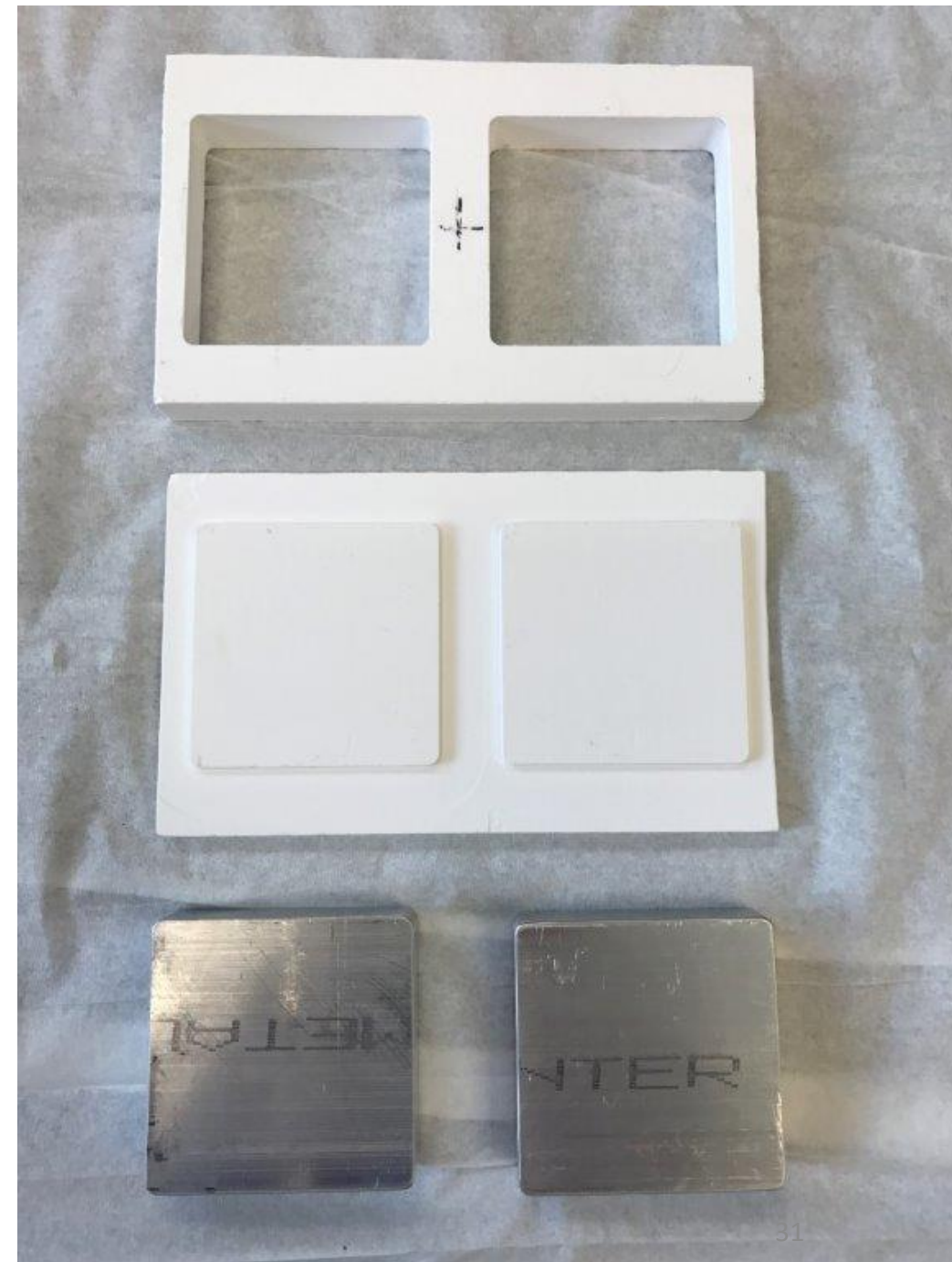
We tried different forces, the left sample was made with 250 kg and the right one with 32.5 kg. The right one is whiter, but weaker. Note that we were able to drill holes in the right one.



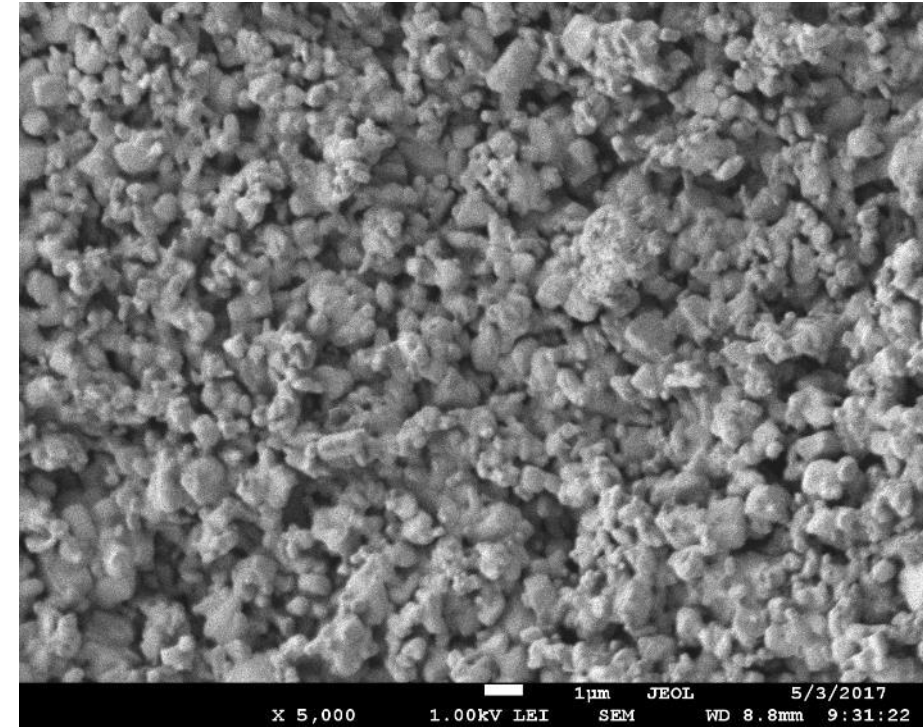
## Cryogenic Selective Surfaces



We tried various molds and have had the best results using ceramic. This allows the samples to be pressed and then fired without having to be removed from the mold.



# Cryogenic Selective Surfaces



Pressed BaF<sub>2</sub> sample using the 2-inch ceramic mold. Note that the resultant samples are slightly curved. SEM shows the particle size and void volume of the pressed sample.

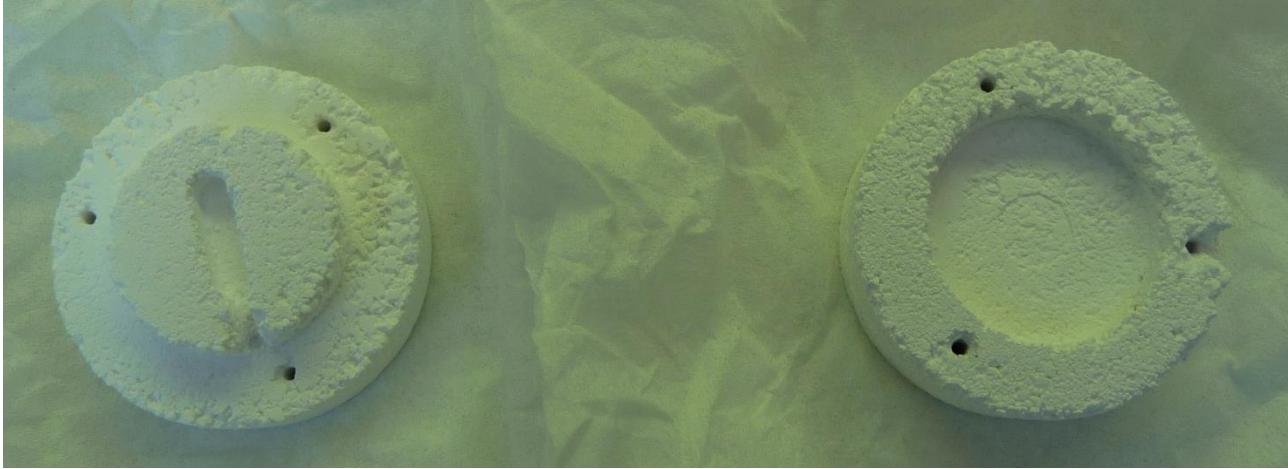


# Cryogenic Selective Surfaces



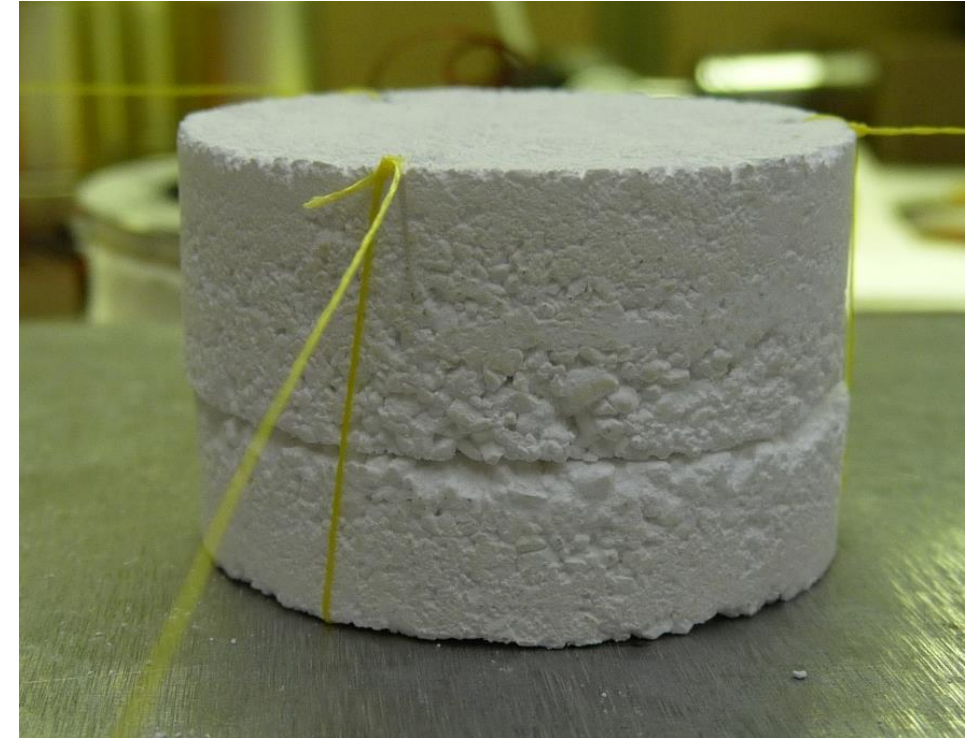
The final surface requires a silver layer under the scatterer to reflect long wave radiation. The image on the left shows a coating fabricated on silver and the one of the right shows silver deposited onto the scattering surface.

# Cryogenic Selective Surfaces



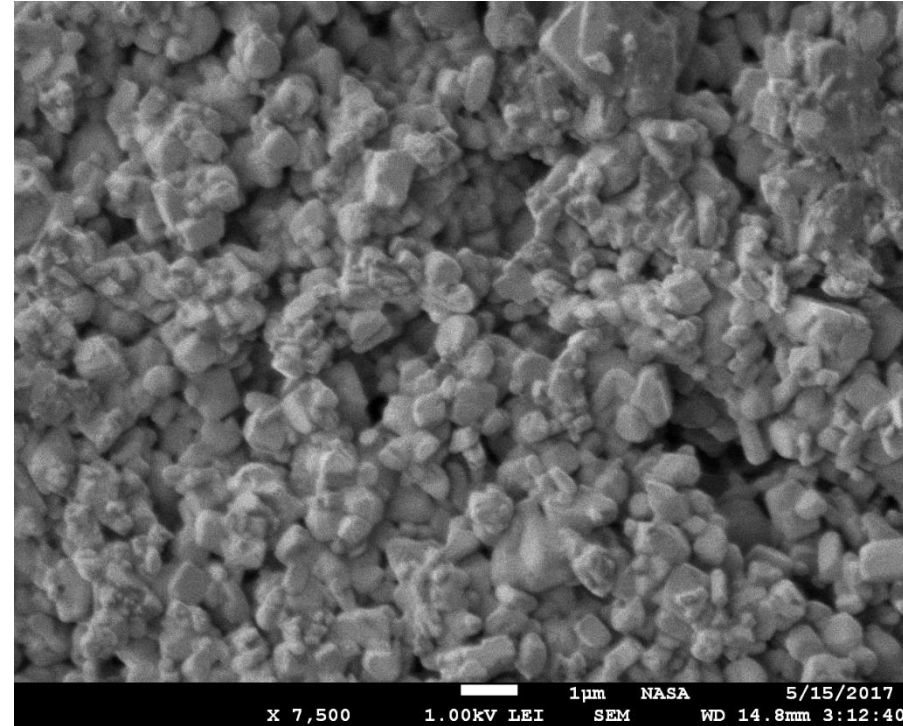
If we can only create small samples they will need to be joined such that radiation can not pass between them.

We have succeeded in machining lips and cutouts. The sample to the right contains a temperature sensor and was used in a recent test.





# Cryogenic Selective Surfaces



This is our best sample to date. It's more than 3 inches in diameter (87 mm), 6-7 mm in thickness.

The optical properties are very good and it appears to be strong.

The SEM shows we've retained the particle sizes, addressing a significant comment from the proposal review.

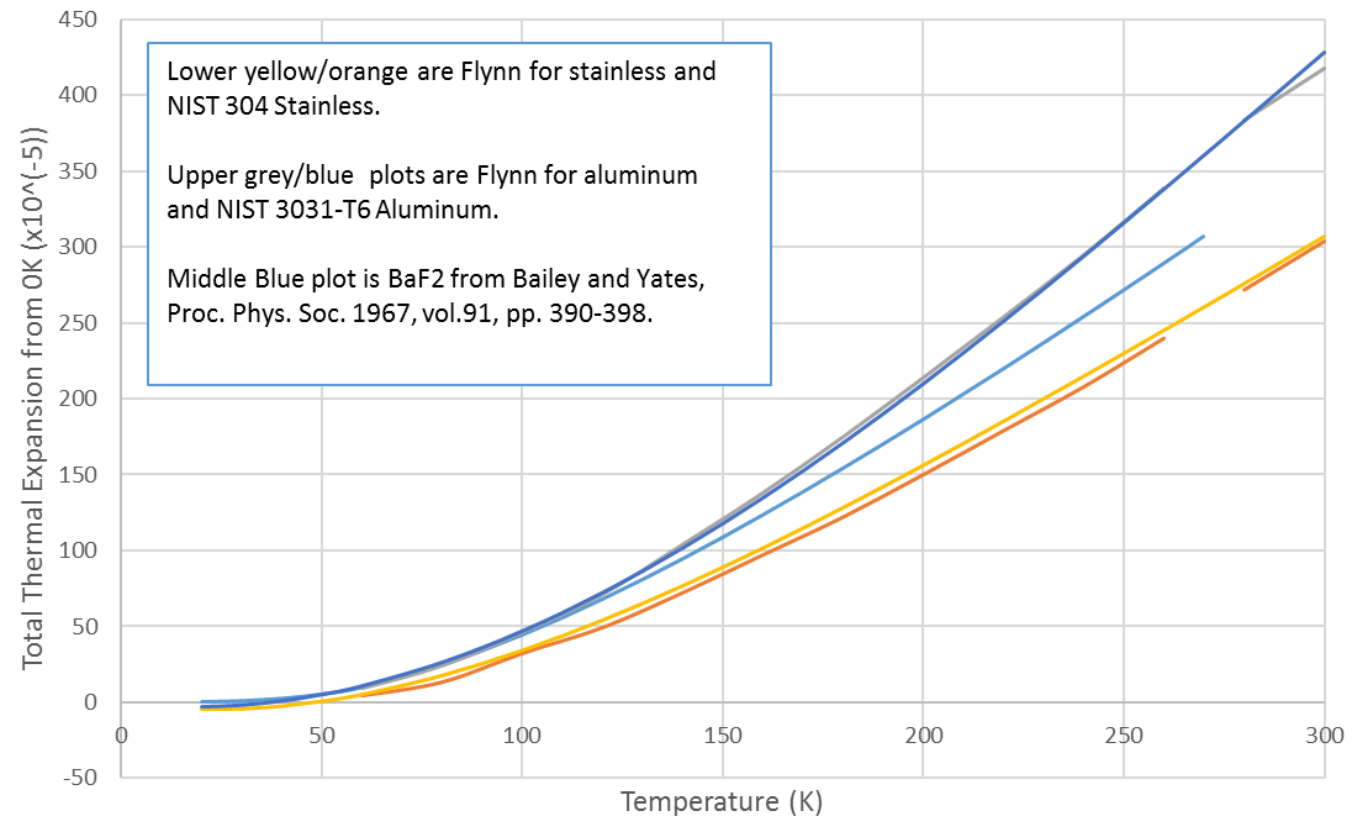
During the coming year we will continue to develop these coatings. We will:

1. Cut out Mohr bars that can be tested in an Instron to determine mechanical strength and properties.
2. Determine through construction and testing the maximum diameter and thinnest thickness we can achieve to meet mechanical and optical parameters.
3. Continue to machine these samples and show that curved surfaces and even cylinders can be covered.
4. Work on adhesion of these samples to metal surfaces. Note the relative thermal expansion plot to the right.
5. The goal is to demonstrate repeatable coatings that can be applied to any surface and survive launch and operate in deep space.

## Cryogenic Selective Surfaces



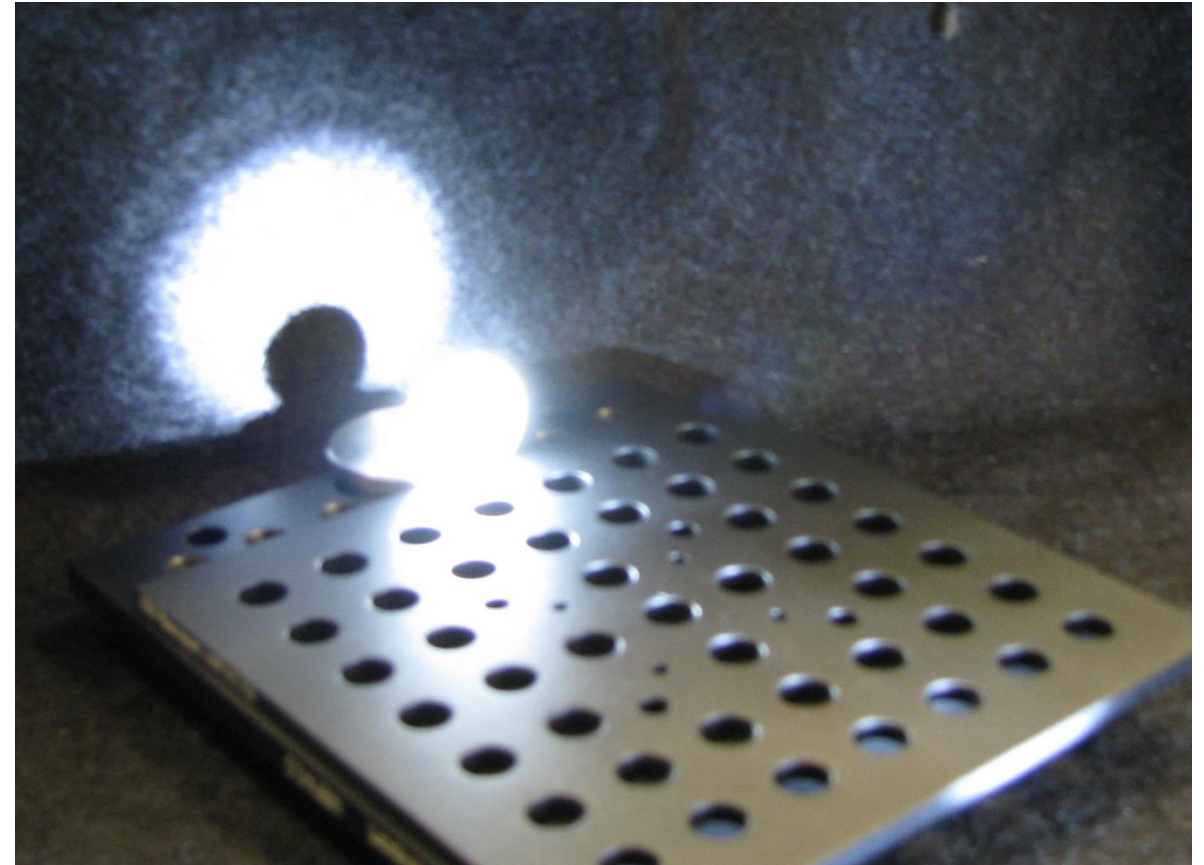
Integrated Thermal Expansion of BaF<sub>2</sub>, 304 Steel, and Aluminum 6061-T6





# Cryogenic Selective Surfaces

First Break—  
Be back in ten  
minutes.



Light scattering off of a pressed NaCl disk.

# Cryogenic Selective Surfaces



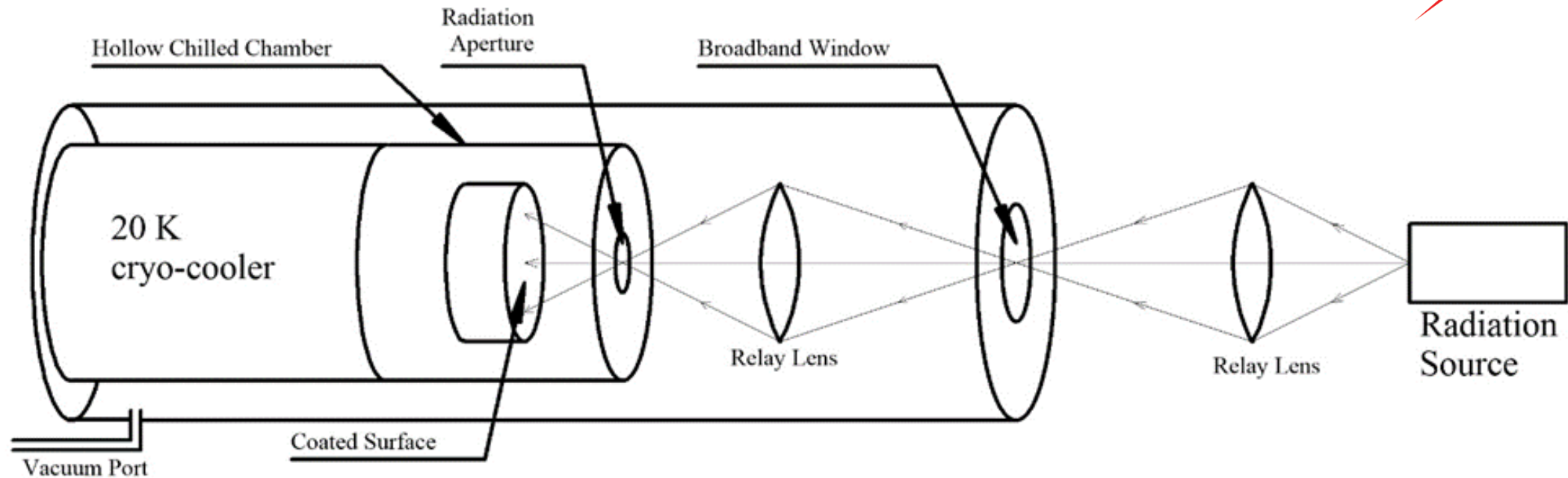
Testing both powder and rigid coatings

The proposal review stated:

**Obtaining data to establish the feasibility/practicality, or lack thereof, of this concept should be the primary goal.**

The best test of the new coating would be to place it in a high fidelity simulated deep space environment and measure the temperature under full solar illumination.

# Cryogenic Selective Surfaces



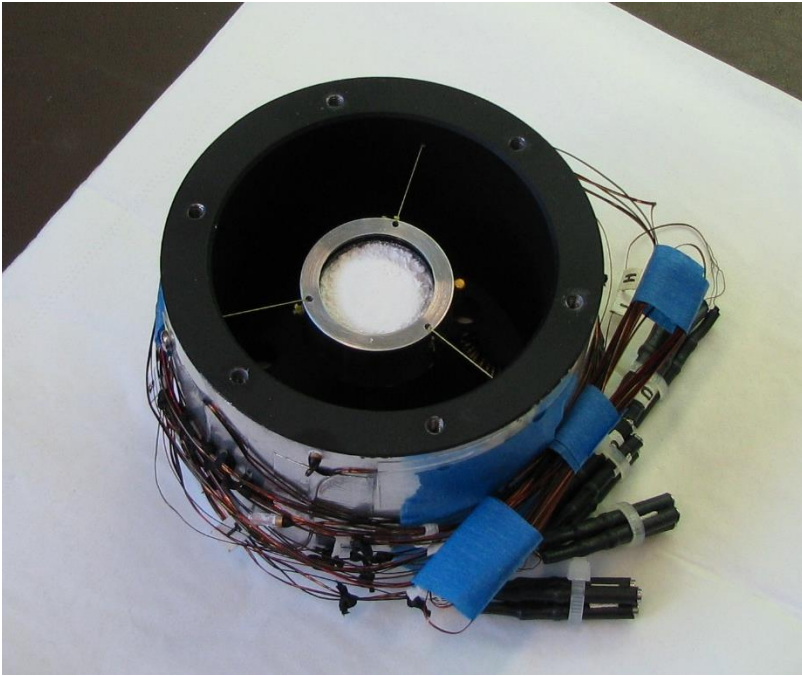
This best test was described in the proposal. A solar simulator would launch light into a very cold vacuum chamber where the sample would be held and its temperature monitored.

However, we were told that the cost and delay in modifying the KSC cryo-chamber was prohibitive, so we had to modify this approach and place the radiation source inside of the chamber. This limited us to low power, small size radiation sources.

# Cryogenic Selective Surfaces

We started in March of 2016 with powder versions of Solar White.

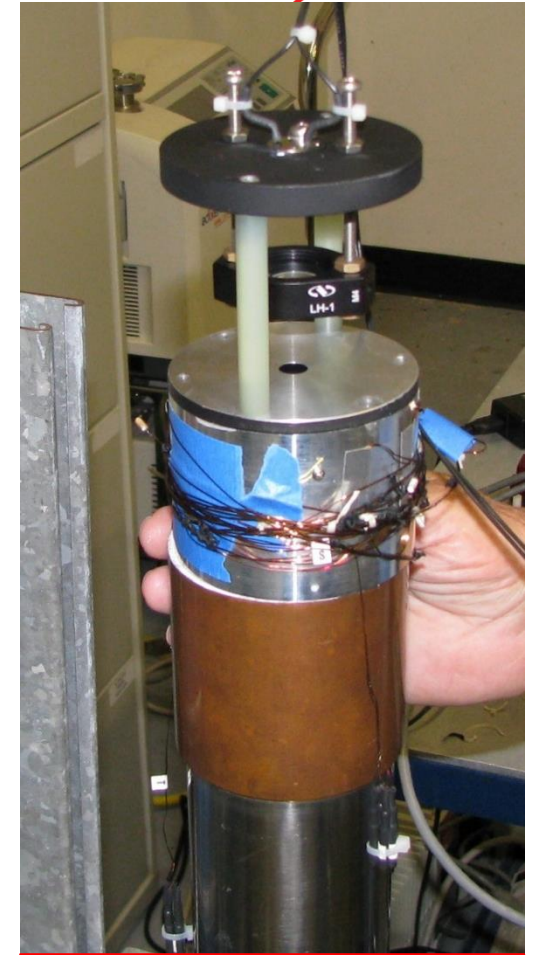
Samples are suspended in a simulated deep space environment (cold vacuum) and then irradiated while their temperature is monitored.



Solar White sample  
suspended in a cold cell.



Light source and lens launching  
radiation into the cold cell



Complete assembly on  
top of a cryo-cooler.



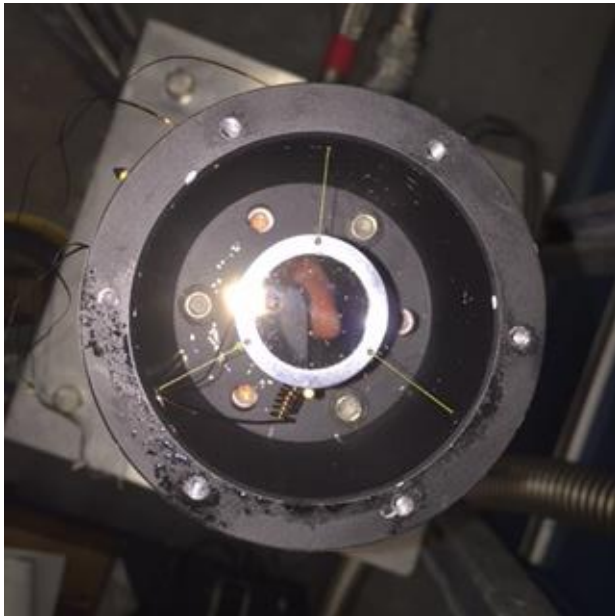
# Cryogenic Selective Surfaces

Things that went wrong—  
and note that each test takes roughly one week to set up and run.

Our first UV Led emitted too little power to be used.

We tried using an IR blackbody and could not reliably  
model this light source and had to give up using it.

We tried an  
organic IR  
background  
and it  
produced oil  
that spilled  
over the test  
cell.



Paint came  
off of the  
cover and  
fell on the  
test cell.



Disconnected wires,  
Temperature sensors fell off during testing,  
Computer turned off during test,  
New UV LED self destructed.

# Cryogenic Selective Surfaces



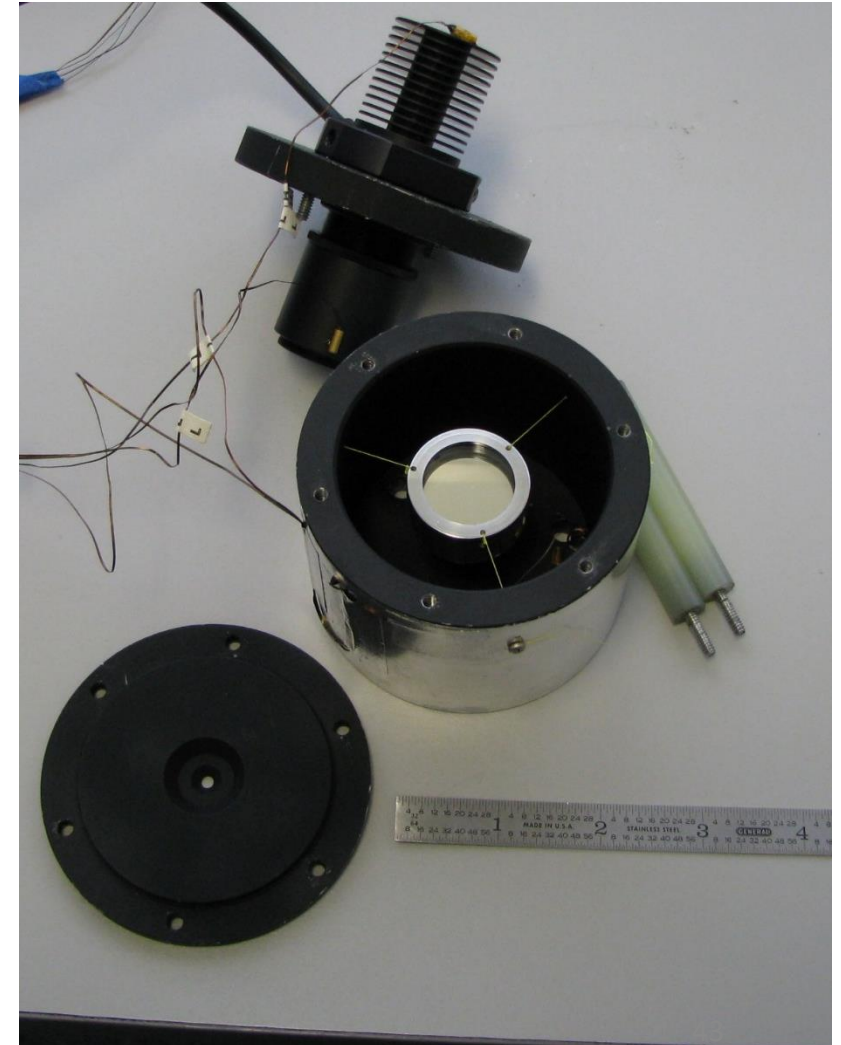
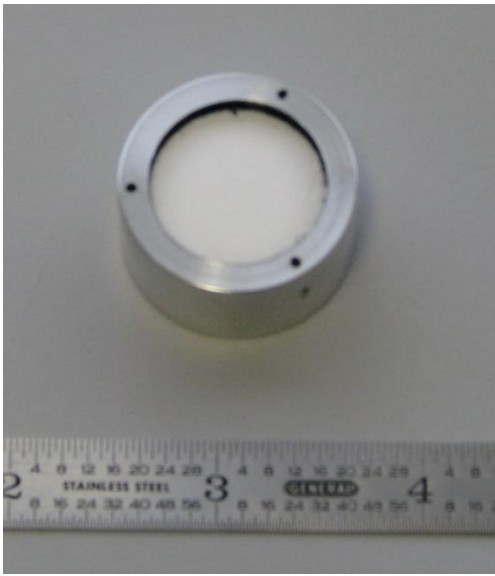
Testing started with a small UV LED, but lack of power and IR emission resulted in inconclusive results.

We moved to a 1000 K blackbody and the results were reasonable, but difficult to quantify.

We then found a high power 375 nm LED from Thor Labs—seen to the left—and have been using this to test our coating.

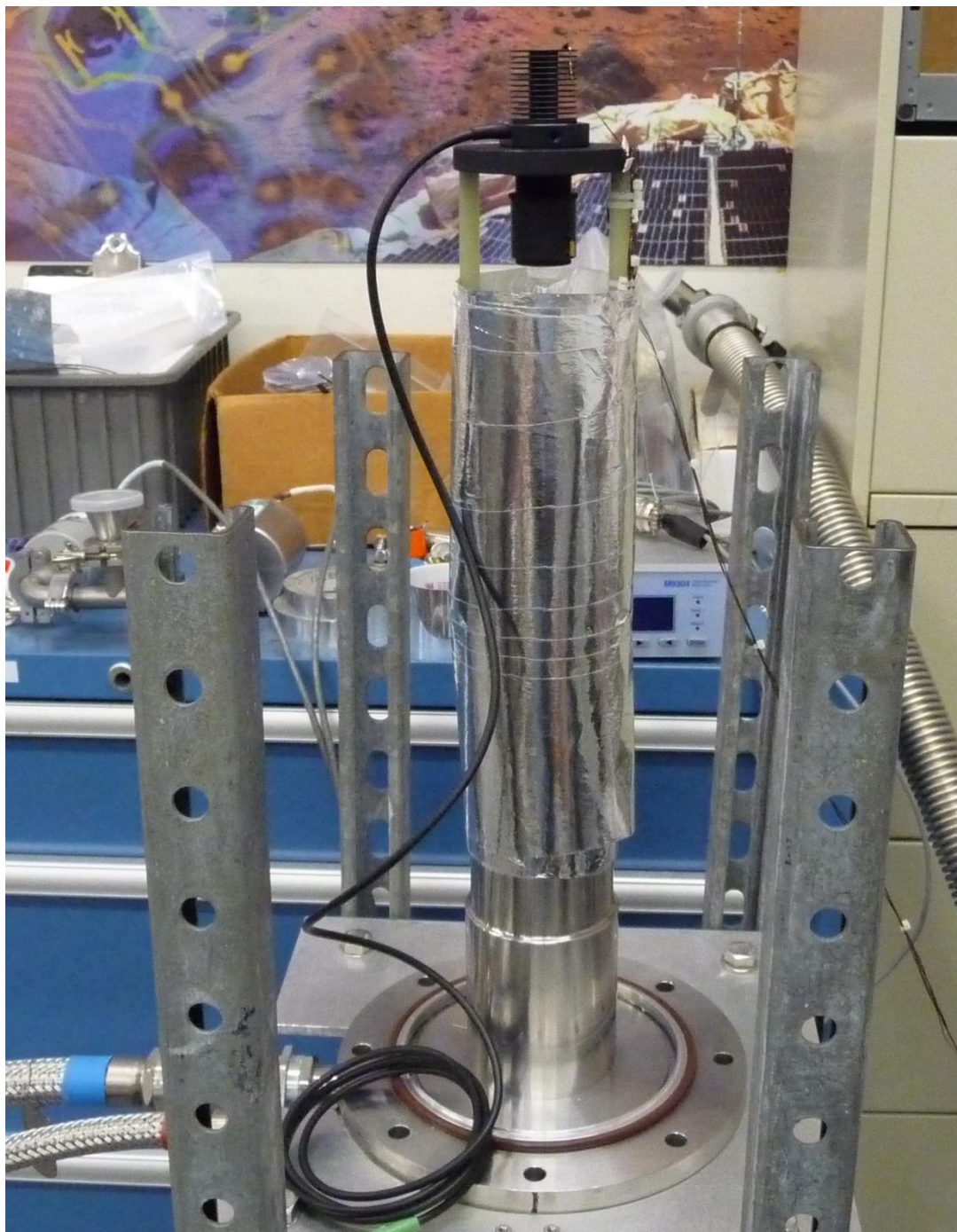
# Cryogenic Selective Surfaces

We finally obtained two good runs using a high power UV LED; one with our new coating and one with a second surface mirror constructed from sapphire and silver. (August 2016).



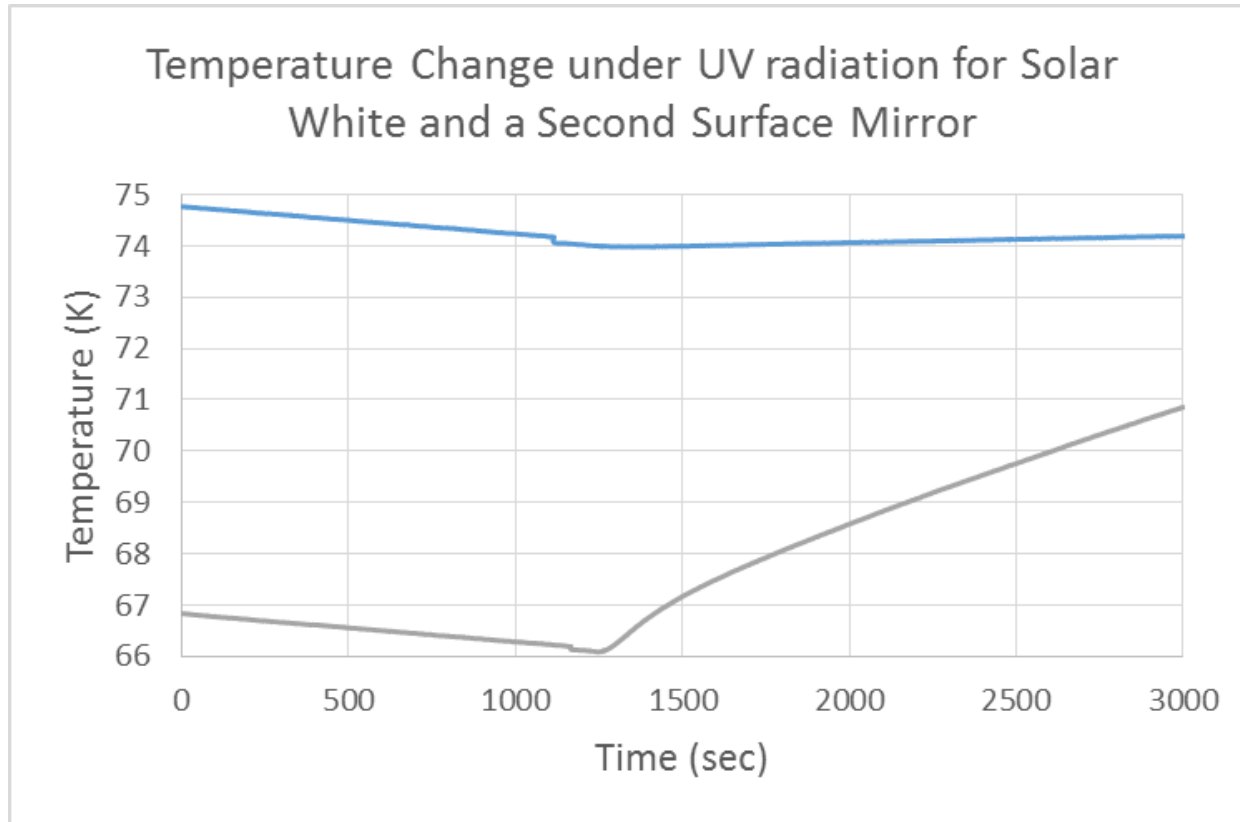


The test system mounted  
on the cryocooler.





# Cryogenic Selective Surfaces

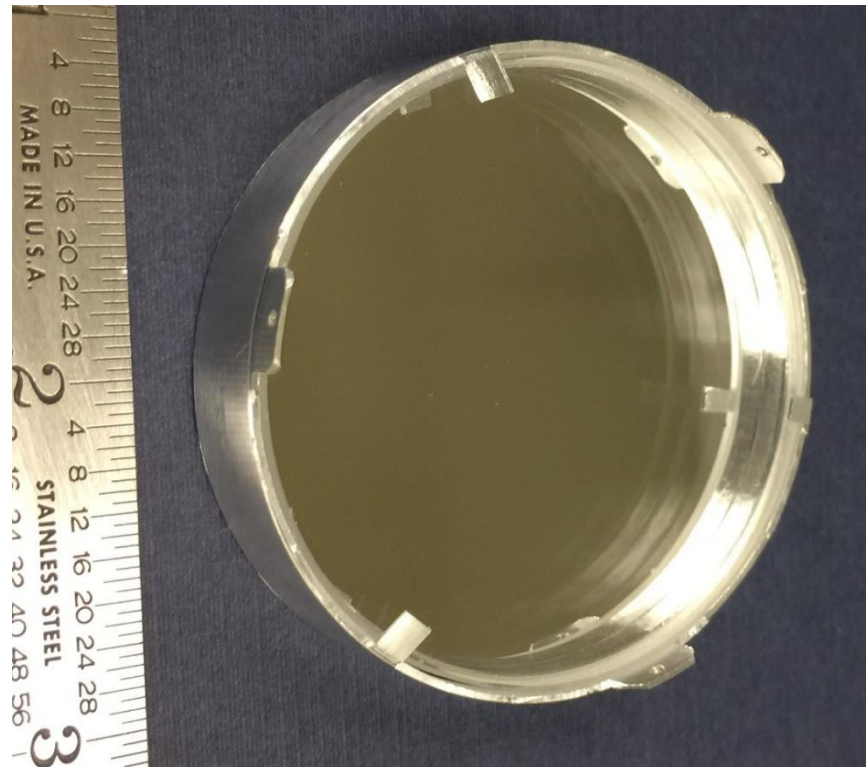
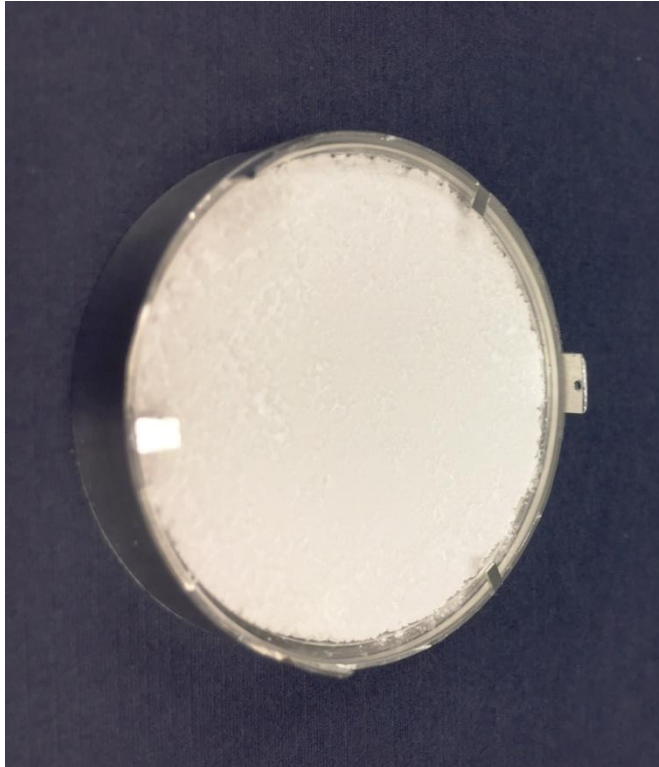


These two plots show the test cells chilling down and then the UV light is turned on at about 1200 seconds.

The lower plot is the second surface mirror. We predicted 7.5 mW absorbed, while the data indicates about 7.9 mW absorbed.

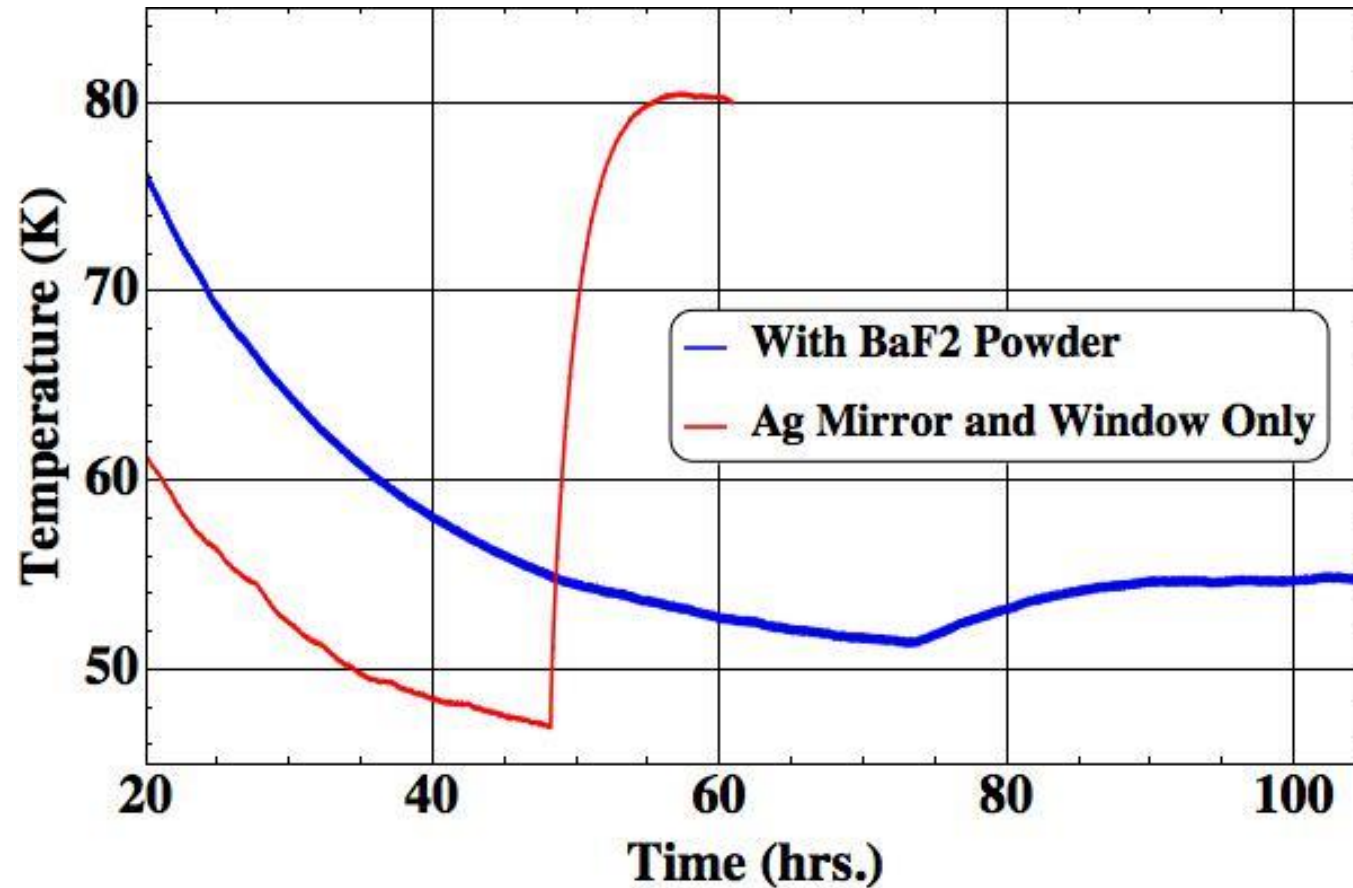
The upper plot is the New Solar White coating. We predict no measureable absorbed power, but see 1.8 mW. We thought this was probably power absorbed by the test cell aluminum walls.

# Cryogenic Selective Surfaces



We decided to try the test again with larger samples in order to minimize the absorption of energy by the aluminum holder. Shown are two identical samples with silver mirrors and BaF2 windows, but one has BaF2 powder added.

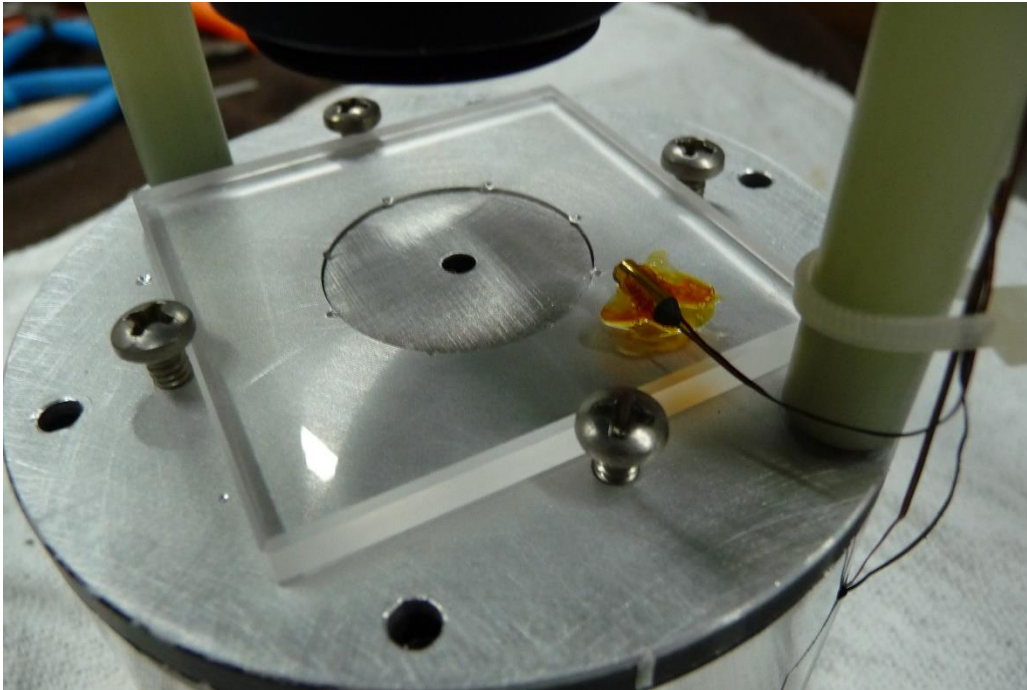
# Cryogenic Selective Surfaces



After accounting for infrared heating, the data shows that the silver mirror absorbed about 17% of the 375 nm UV radiation (the published number is 18%) while the powder filled sample absorbed less than 1%.

This is a substantial verification, but we can do better.

# Cryogenic Selective Surfaces

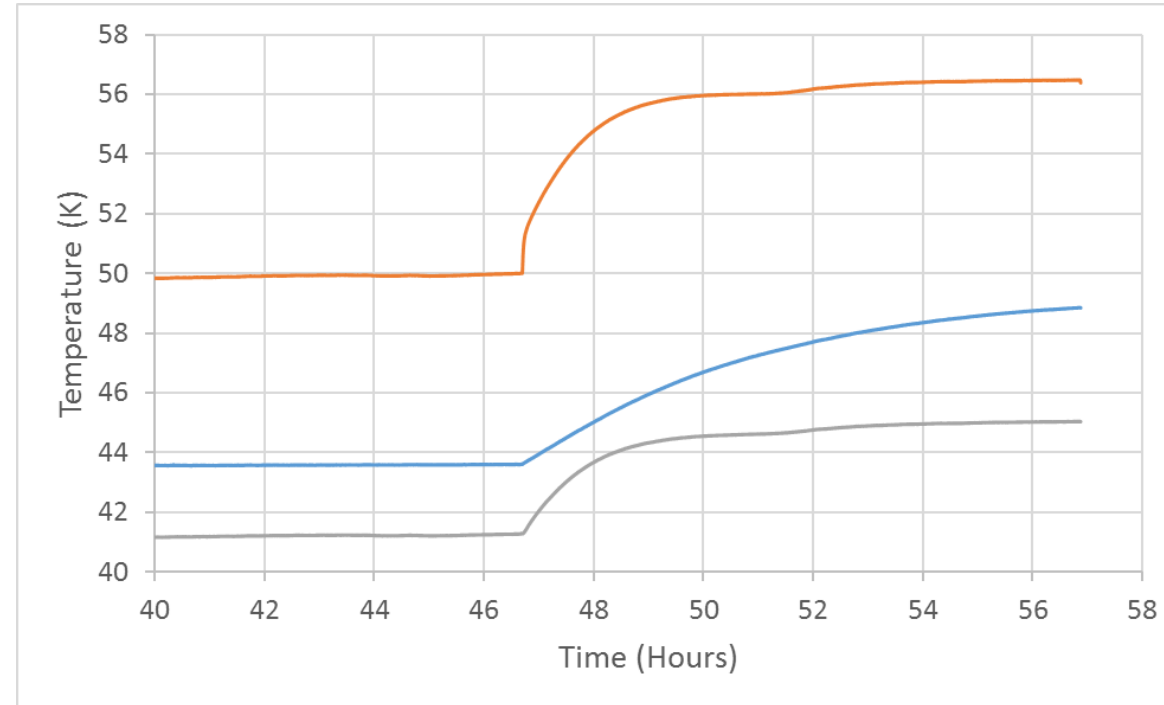
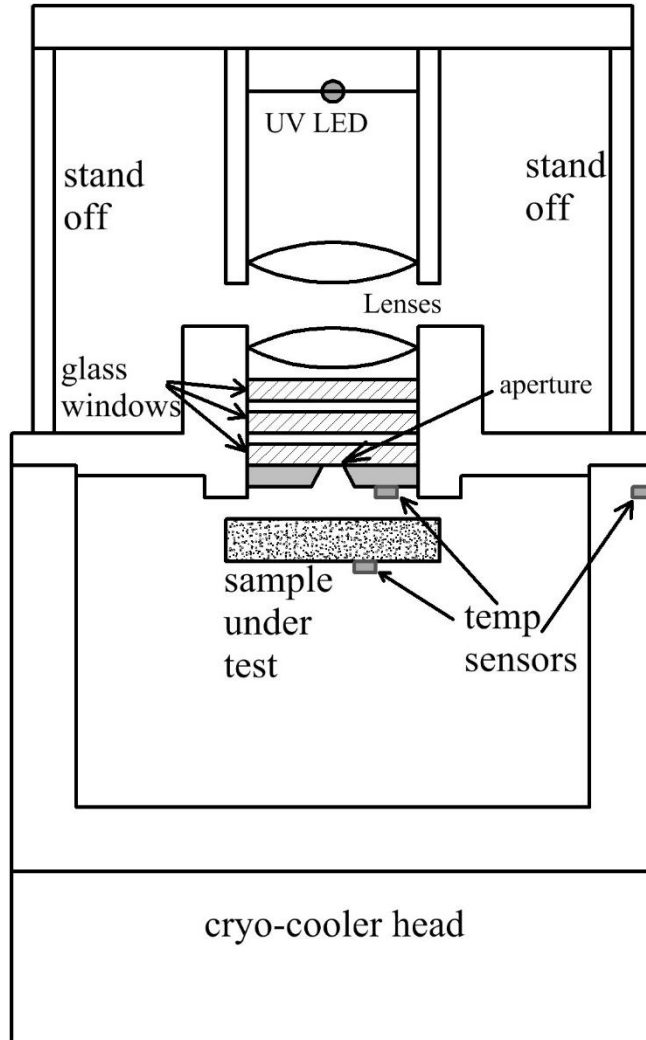


I remembered someone at the NIAC symposium suggesting the use of an IR shield. I decided that this was worthwhile and tried to implement it with the sapphire window shown to the left.

Sadly, this failed since the window itself got hot. However, it led to our most recent design where we have multiple windows.



# Cryogenic Selective Surfaces

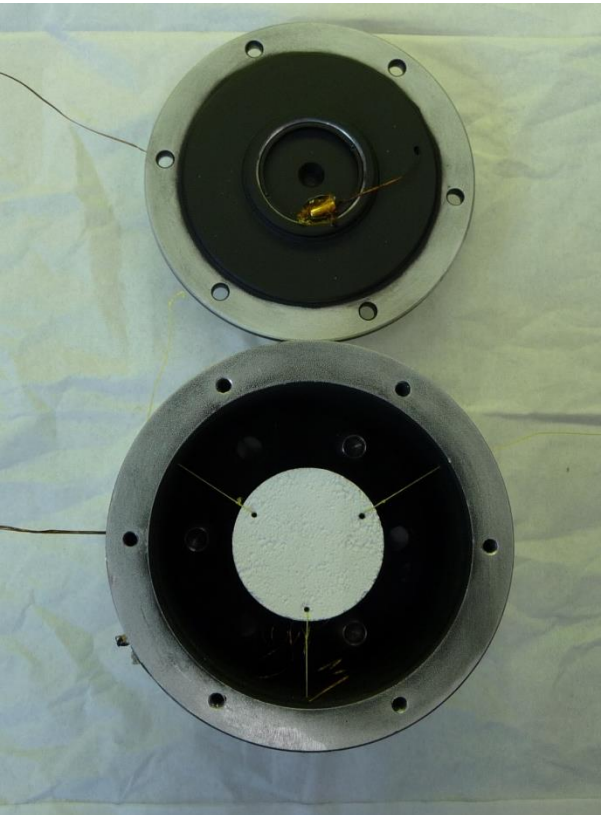
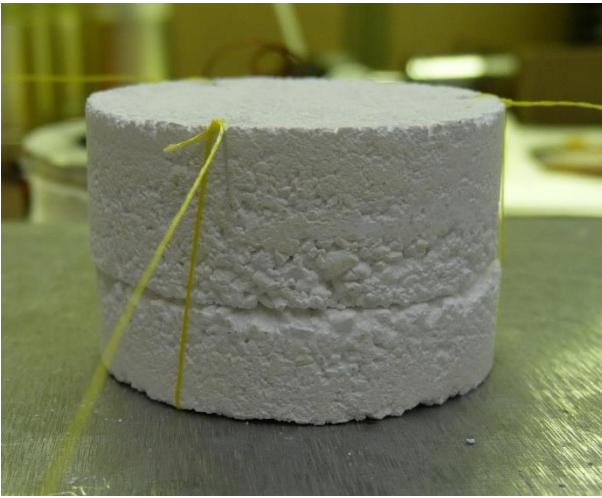


Grey is the wall temperature.

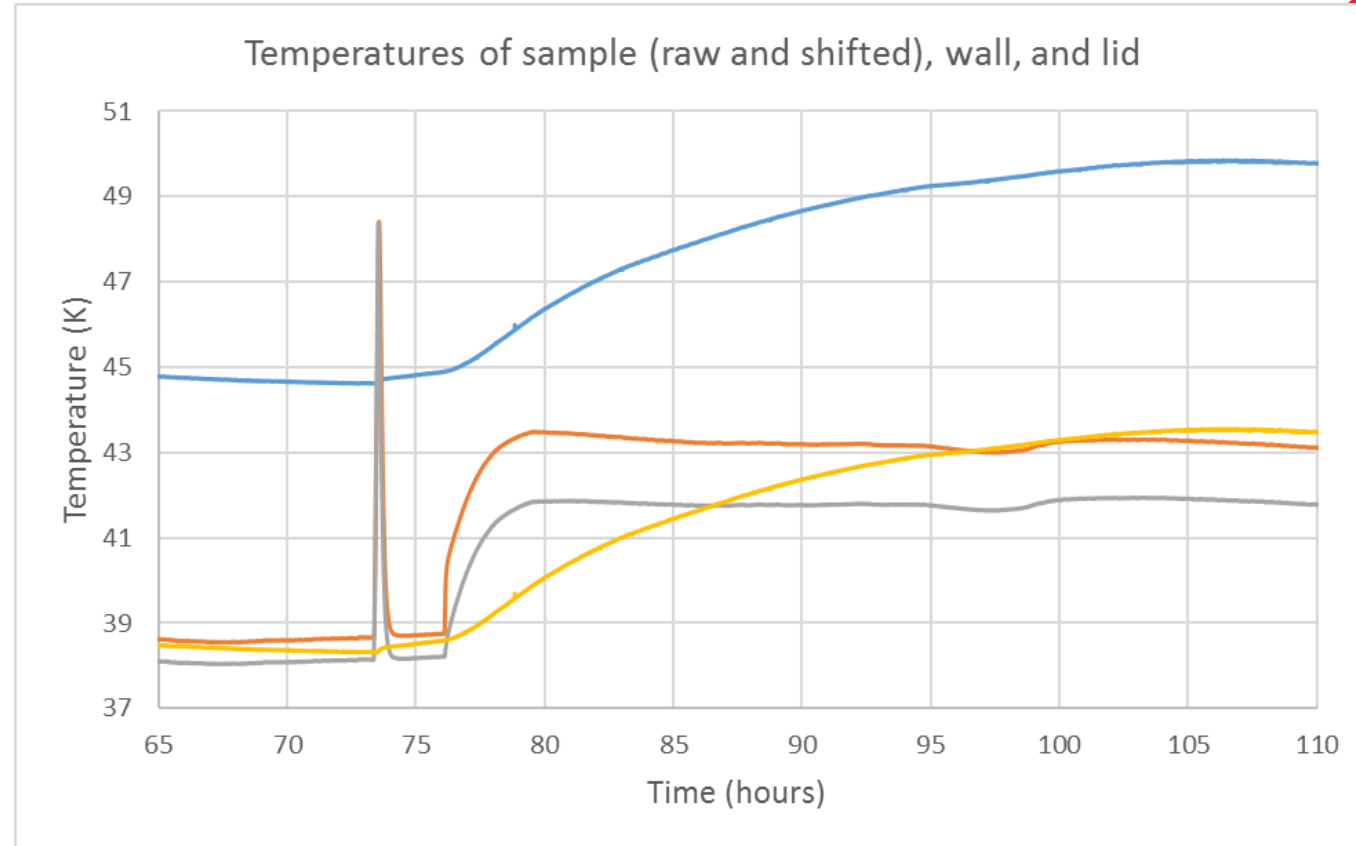
Orange is the lid temperature.

Blue is the sample temperature.

This worked well. The sample absorbed less than ¼% of the illumination. It is staying under 50 K while being illuminated with 17,000 microWatts of 375 nm radiation. However, the lid and chamber are at very different temperatures due to paint issues, so we can do better.



# Cryogenic Selective Surfaces



Grey is the wall temperature.

Orange is the lid temperature.

Blue is the sample temperature.

Yellow is the sample temp. Shifted.

We removed the excess paint and packaged the temp sensor in the coating material—one more step towards a real version. However, now sensor heating has become an issue, so we are rerunning this test, pulsing the sensor on less than 1/100th of the time.

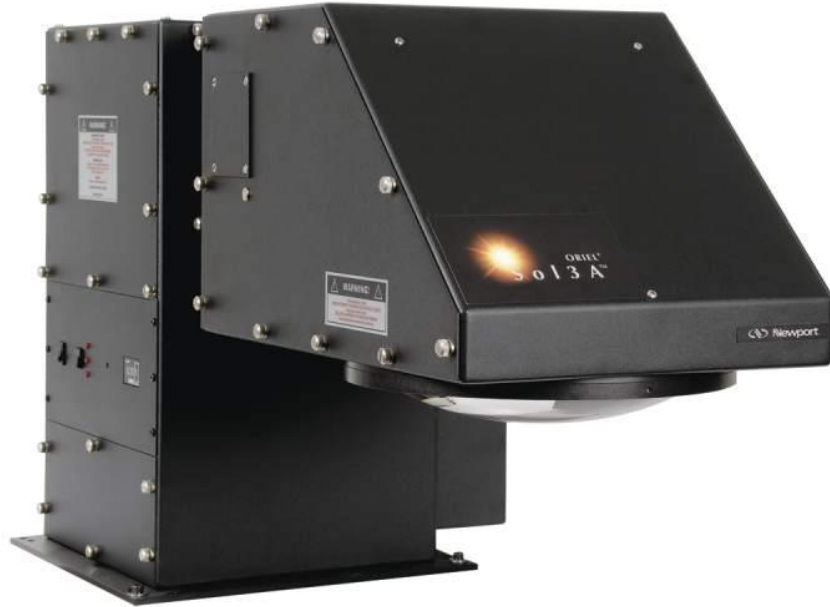
# Cryogenic Selective Surfaces



In summary:

1. We have worked diligently to test the new coating.
2. To date the new coating is behaving as expected and we have verified that it absorbs less than ¼% of 375 nm radiation, but we should be able to do better.
3. We have significant understanding of the infrared aspects of the coating.
4. We have learned how to do low temperature absorption testing and now feel ready to start development of a higher fidelity test chamber (at GRC).
5. We have made significant progress in using Thermal Desktop to model our experiments.

# Cryogenic Selective Surfaces



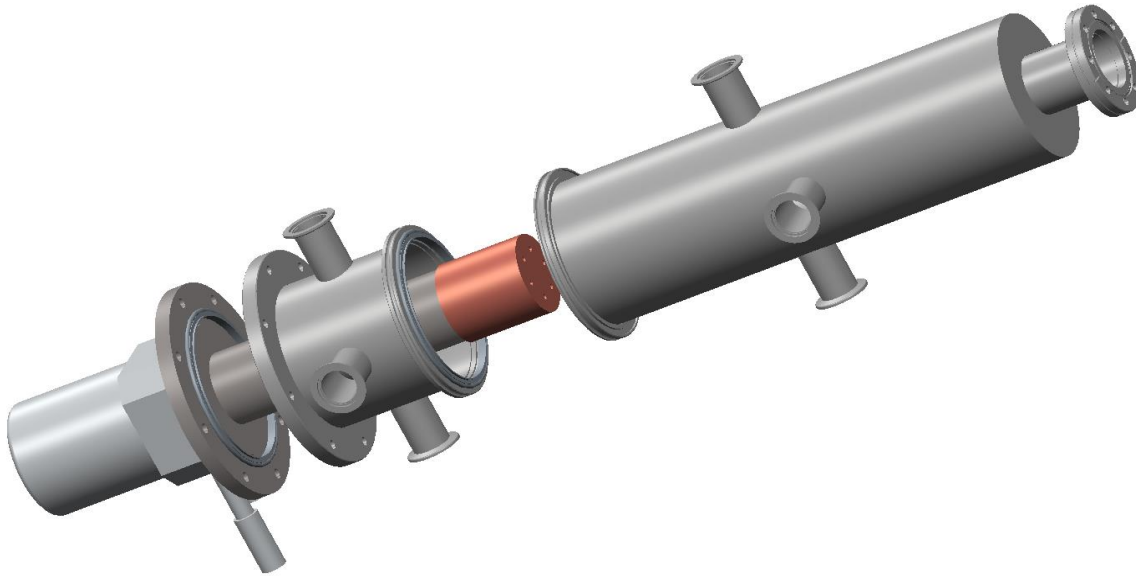
Newport Solar Simulator

A key goal during the next year of the NIAC project will be to test our coating in a deep space simulated environment with full solar illumination.

Using Game Changing funding with some NIAC FTE we plan to design and build this chamber at Glenn Research Center (Wesley Johnson).



# Cryogenic Selective Surfaces



We recently found a route where we can construct a small scale deep space simulator with a solar simulated light source here at KSC. We'll construct a new vacuum chamber with a sapphire viewport and then use a Xe discharge lamp as a radiation source. This system is under construction and we hope to begin testing in August.



Break point if needed.

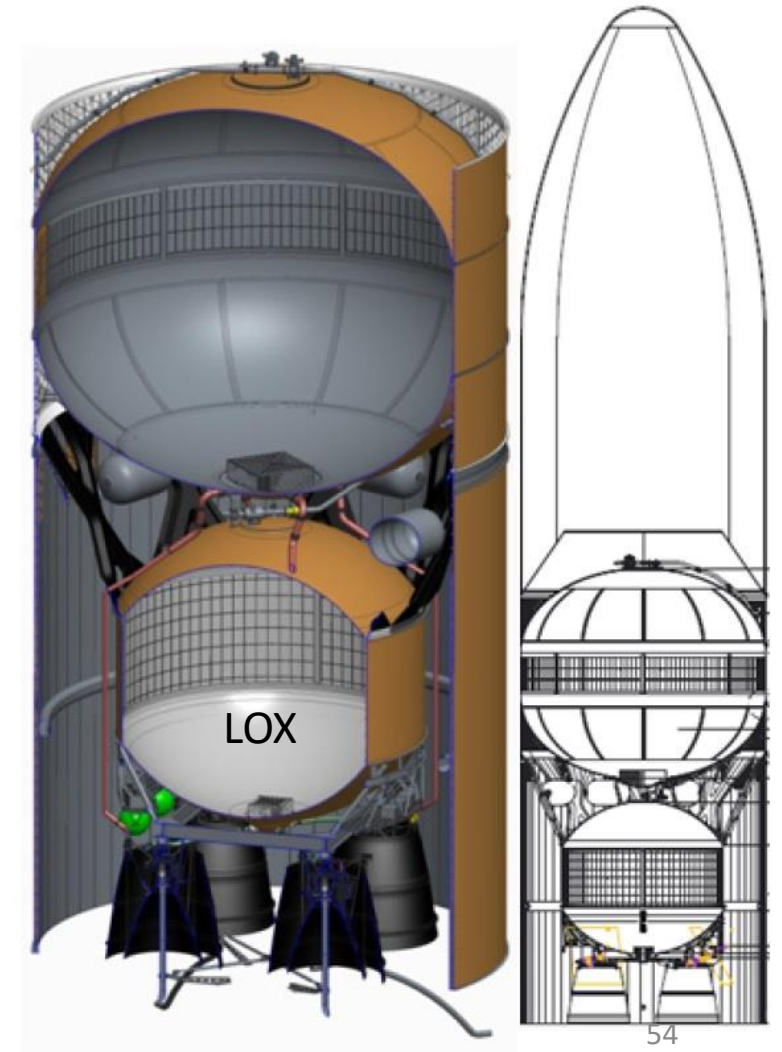
# Cryogenic Selective Surfaces

## LOX in Space

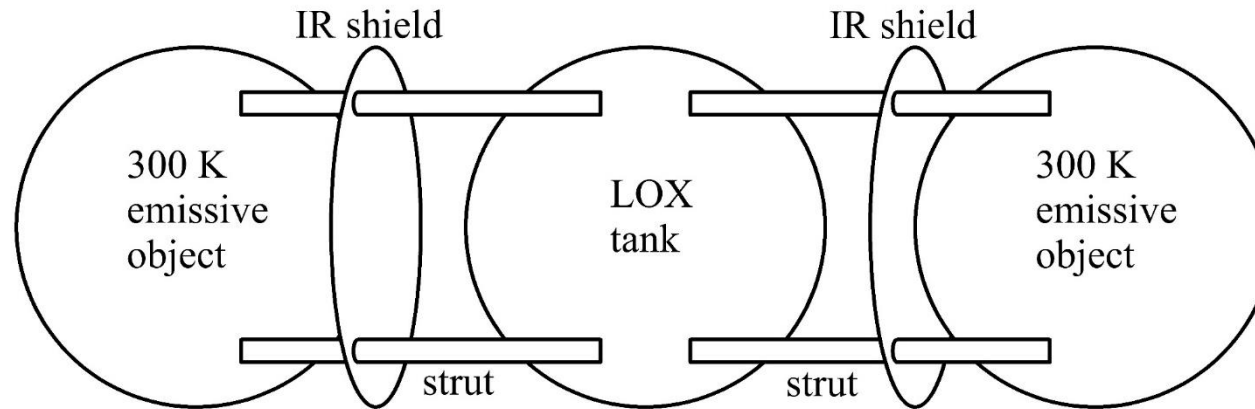
The proposal review stated that:

**The resulting benefit** (of this new concept) , **to propellant depots, extraterrestrial bases, and long term space travel, is far reaching.**

With that in mind our primary mission application of this new coating has been to determine if LOX can be taken to Mars and then to extend this to propose a possible LOX storage depot on the Moon. In addition we've been looking at LOX storage in low Earth Orbit for the Launch Services Program.



## Cryogenic Selective Surfaces



We've chosen to model a Mars vehicle as having a LOX tank located between two warm objects, potentially crew quarters and a fuel tank or engine.

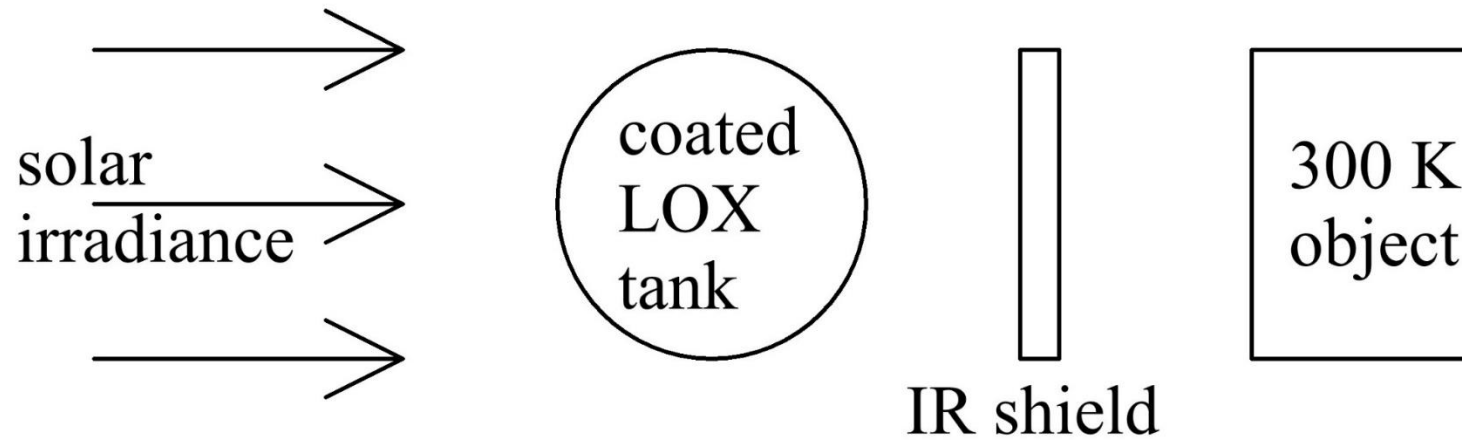
Heat can reach the LOX tank through solar radiation, IR radiation from the rest of the spacecraft, conduction through the struts and connections, and IR radiation from nearby planets.

A black LOX tank (about 95 K) radiates about 4 Watts/m<sup>2</sup>, so the net heat flow to the tank must be less than this to prevent boil off.

LOX in Space

Infrared Shield

## Cryogenic Selective Surfaces



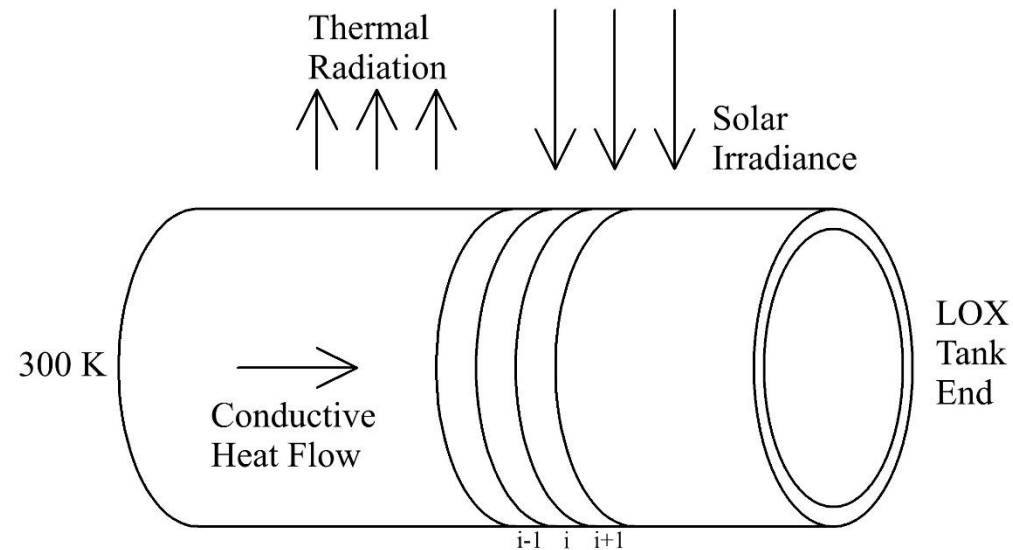
Our new coating will absorb infrared radiation, so an IR shield is needed. This can be a sheet of silver coated Teflon (such as that used on the Orbiter). The plastic side faces the 300 K object so the low emissivity silver side faces the LOX tank. This can reduce the IR heat load by a factor of fifty (or more) depending on specific emissivities and geometry details. However, some of the IR emitted by the tank is reflected back at it and additional solar irradiance is reflected onto the tank.



LOX in Space

Strut Coating

## Cryogenic Selective Surfaces

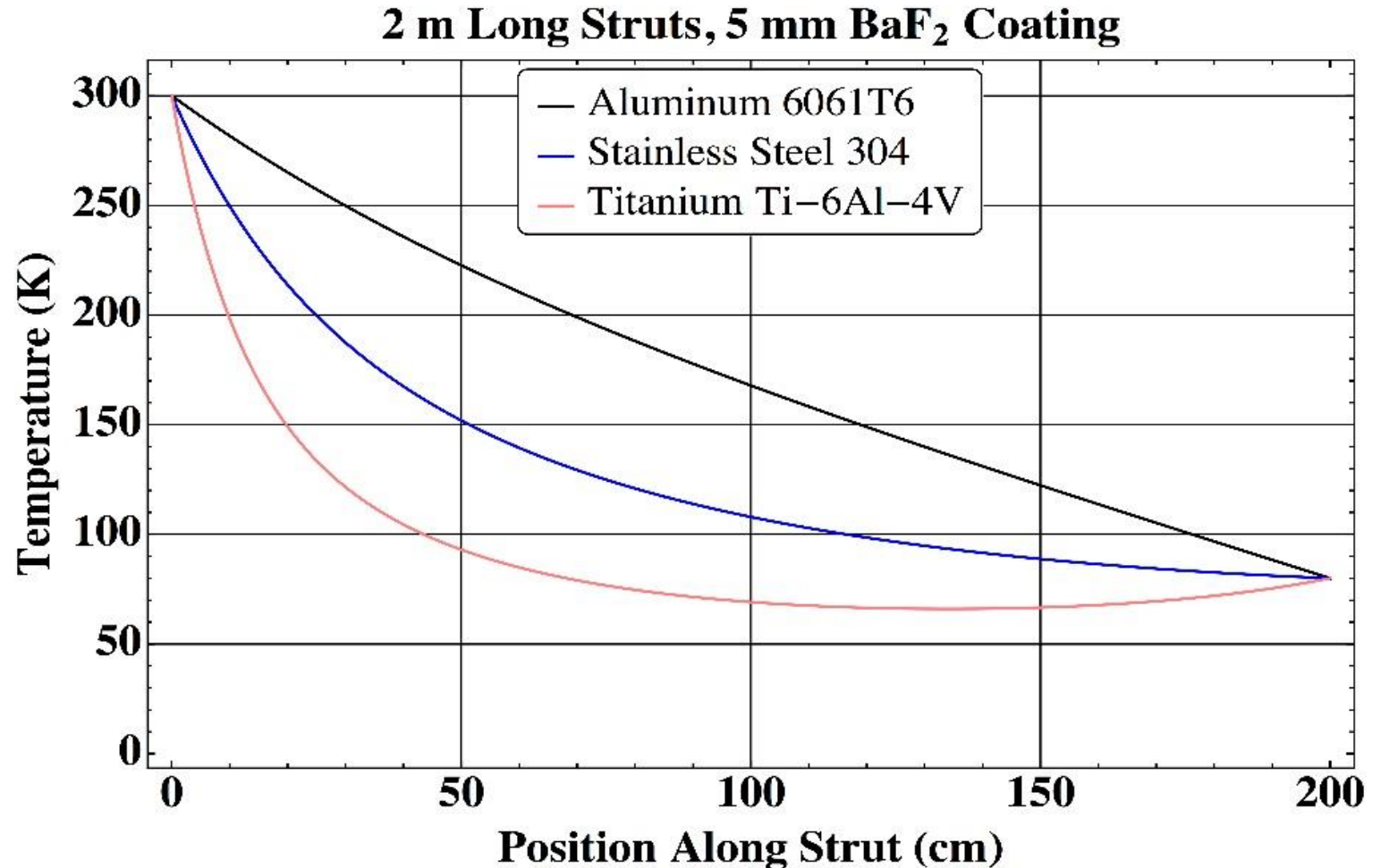


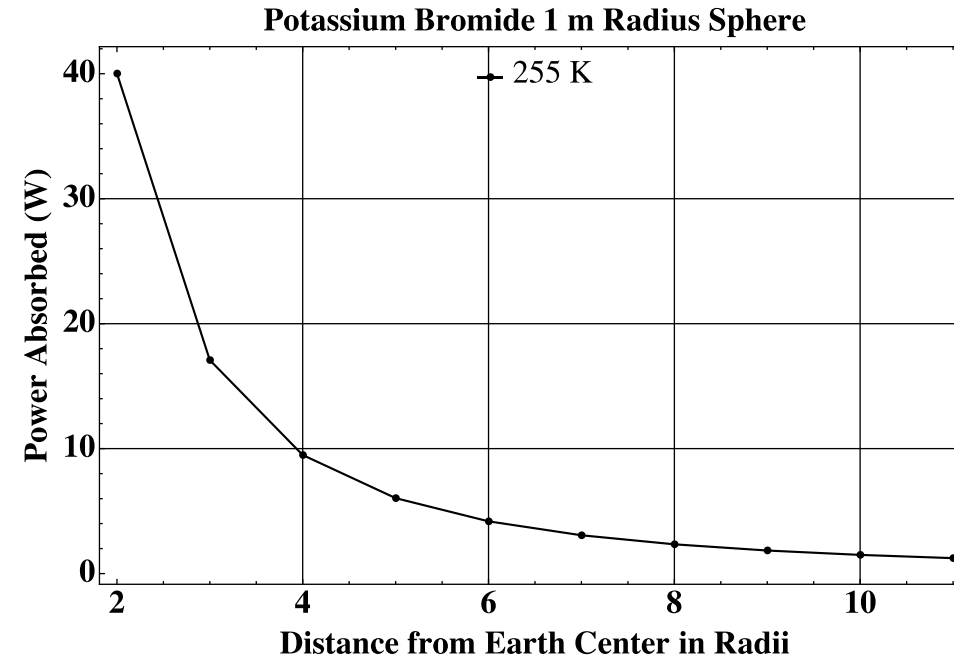
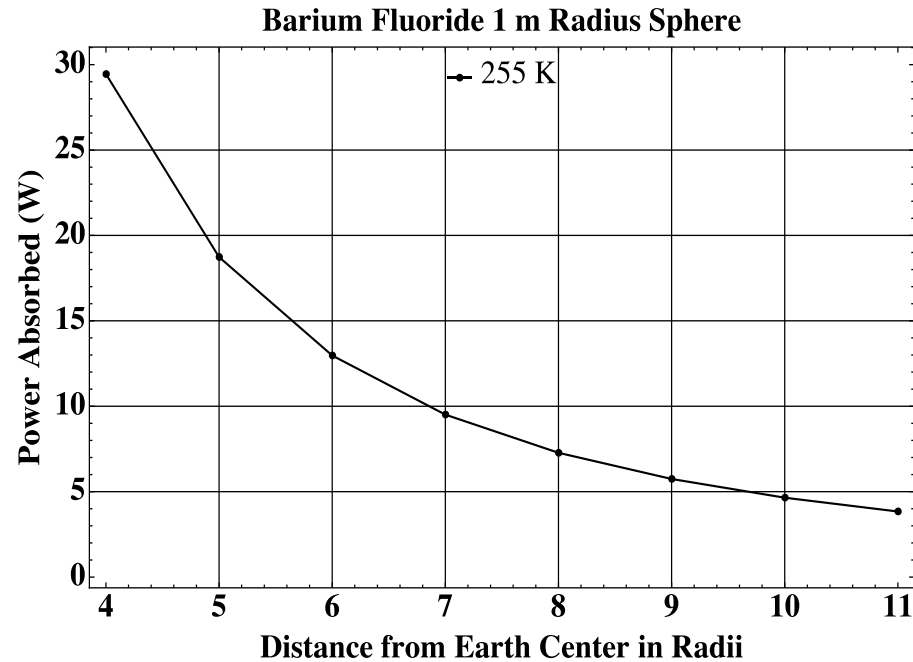
A primary source of LOX tank heat is conductive heat flow along the support struts. If the struts are covered with our coating then solar heating is minimized and the heat in the struts can radiate away. The question is, can sufficient heat be radiated before it reaches the LOX tank? We modeled a strut as a series of thin rings and included the thermal conductivity of the coating itself (about 0.21 W/m-K).

# Cryogenic Selective Surfaces

The temperature along the strut is calculated for three different metals, showing that substantial heat will be carried to the LOX tank for aluminum struts, but that for titanium struts a small amount of heat will be pulled away from the LOX tank.

Struts are hollow cylinders 2 m long, 0.25 m OD, wall thickness 8.2 mm for Al, 7.1 mm for stainless, and 2.4 mm for titanium (220 kN per strut, 1.4 safety margin).





Planetary infrared heating is a serious issue. The charts above show the absorbed power of a 1 meter radius sphere in orbit about the Earth. A 1 meter radius sphere containing LOX emits about 50 Watts and absorbs about 3 Watts of the Sun's power, so the sphere can get within a couple of radii of the Earth's surface (closer with KBr), but we can not be in low earth orbit without an infrared shield between the tank and the Earth.

# Cryogenic Selective Surfaces

Mission Goal: To transport LOX to Mars

Power Budget with radiation shields for a 5 mm BaF2 Solar White Coating-2 m radius tank.

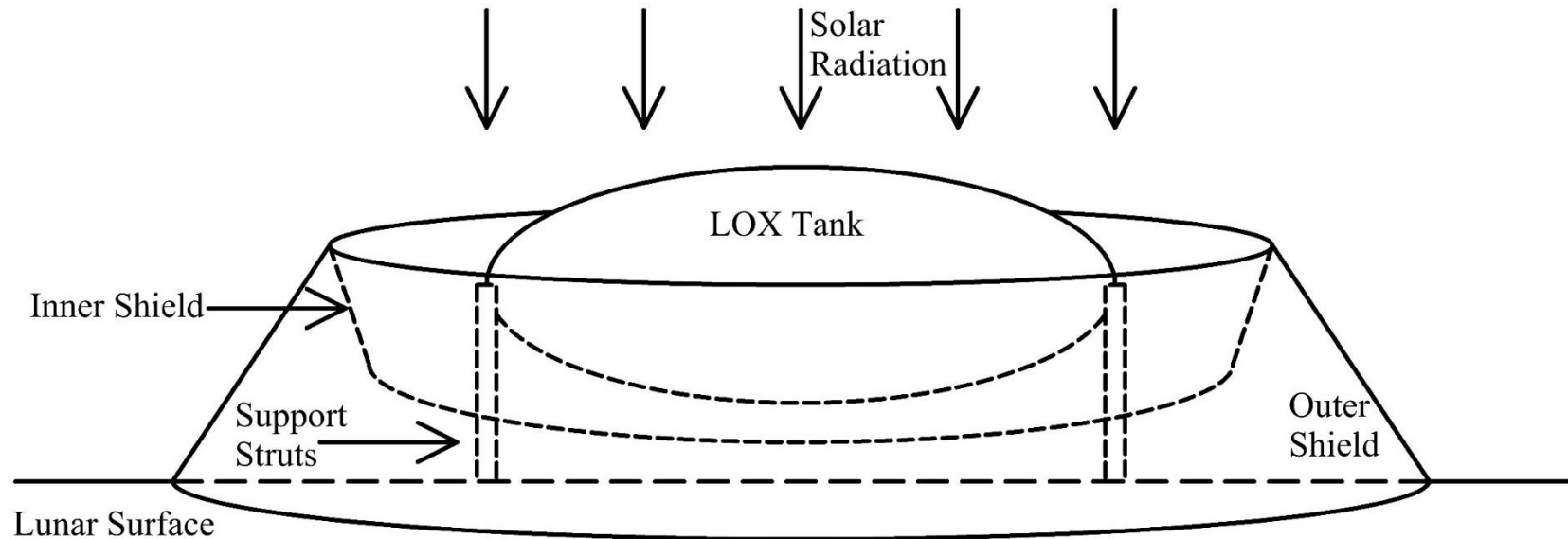
Solar Irradiance-no shadowing	13.5 Watts
IR Load from the shields (assume 0.02 emissivity, 270K, ½ of the IR emission from the shields hits the tank)	45 Watts
Struts (Titanium)	0 Watts
Fuel line	3 Watts
Planetary infrared radiation (assume far from planet)	0 Watts
<b>Total</b>	<b>61.5 Watts</b>
<b>Total Power Radiated at 95.6K (¼ blocking by shields)</b>	<b>150 Watts</b>

Our analysis has demonstrated that with this new coating that LOX can be taken to Mars. In fact, analysis has shown that the LOX might freeze as the vehicle moves away from the Sun.



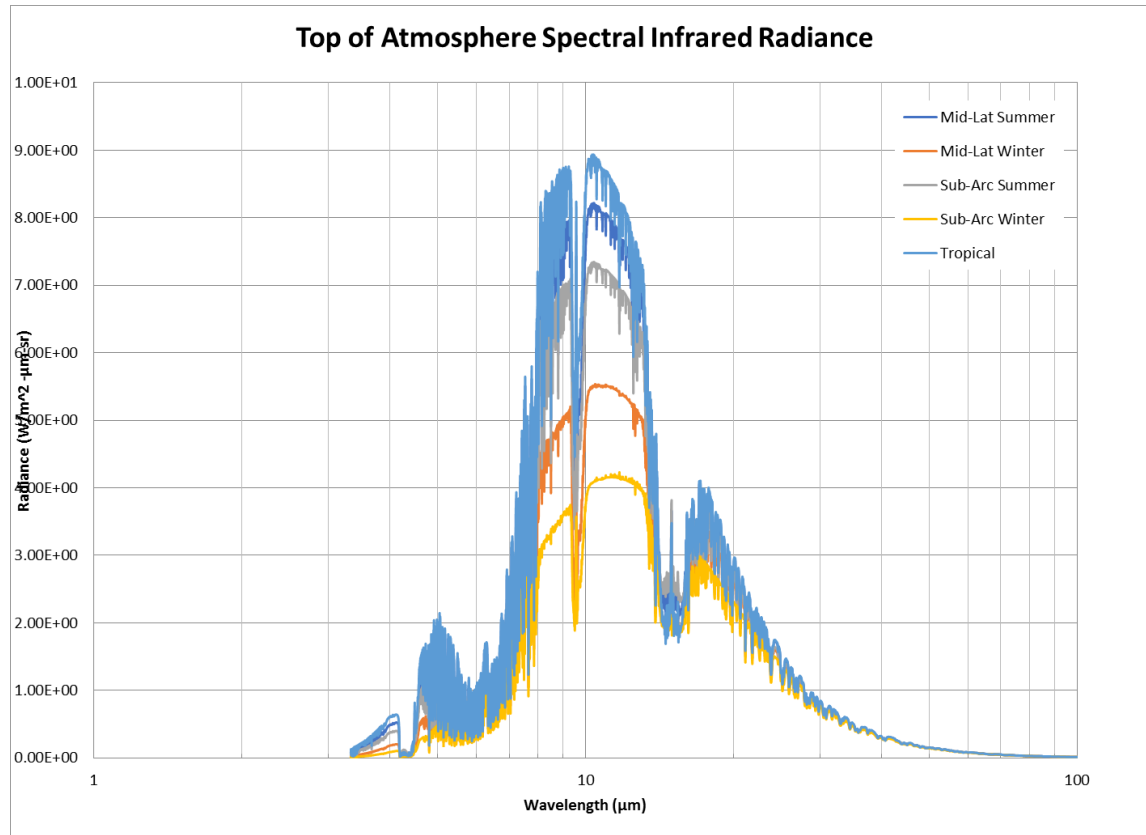
Can we store LOX on the Moon?

## Cryogenic Selective Surfaces



Here is a possible configuration where LOX can be stored on the Moon.

The LOX tank and the support struts are coated to reflect sunlight. Dual infrared shields are used to block the infrared radiation from the Moon's surface. Note that surface under the shields will become cold, minimizing any heat conducted along the struts.



We've received funding from the Launch Services Program aimed at storing LOX in low Earth Orbit.

We've shown through modeling long wave materials such as KBr and CSBr that our coating will not provide adequate blocking by itself.

We are now starting to consider a composite solution to this problem and will return to this in the future work section.

## Cryogenic Selective Surfaces

Second Break—  
Be back in ten  
minutes.



Light scattering off of a pressed NaCl disk.

# Cryogenic Selective Surfaces



## Presentation Outline:

11:00-11:15	Other applications of this new coating
11:15-11:25	Plans for the second year
11:25-11:40	Plans for beyond NIAC, Game Changing, eCryo, and Launch Services Program
11:40-11:45	Finances
11:45-12:00	Open Discussion



From the proposal review we were cited with the following weakness:

**Also the application to superconducting systems is not discussed in detail, and this could, in the far term, out balance the liquid oxygen needs of a spacefaring civilization.**

So let's discuss this:

## Other applications

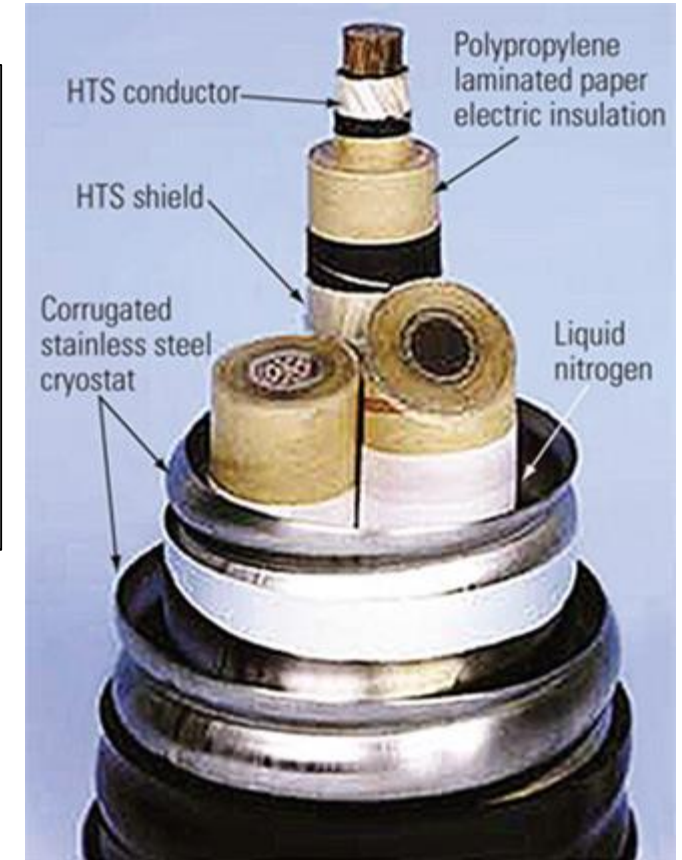
# Cryogenic Selective Surfaces



YBCO (yttrium barium copper oxide) superconducting ribbon becomes superconducting at 90K.

With the proposed coating it should be possible to maintain high temperature superconductors well below their critical temperature.

This would allow lossless current/power flow in space.



LN2 superconducting cable

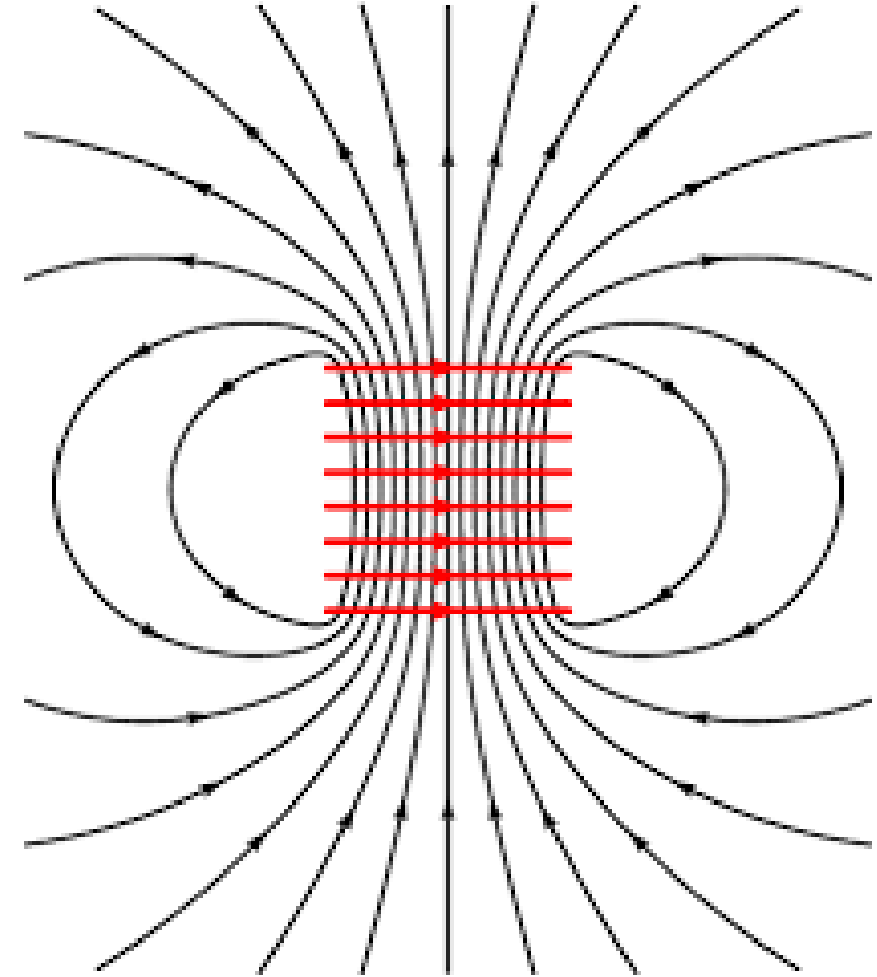
Other  
applications

# Cryogenic Selective Surfaces

## Energy Storage

At 40-50 K superconducting magnets can be used to store energy in space (superconducting magnetic energy storage-SMES).

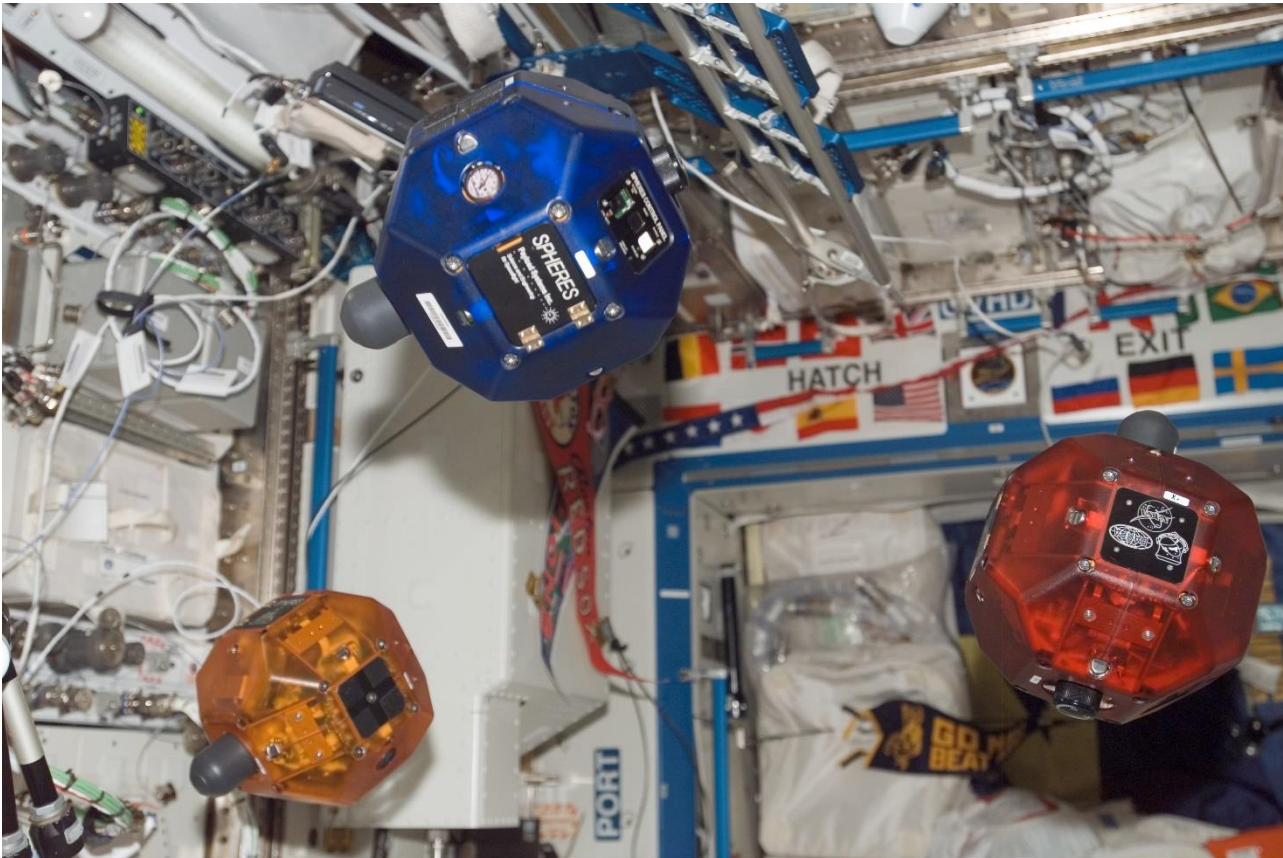
The Florida Institute of Technology (FIT) has been proposing to develop a space rated SMES using our new coating.



Other  
applications

# Cryogenic Selective Surfaces

Novel Concepts



ISS014E17875

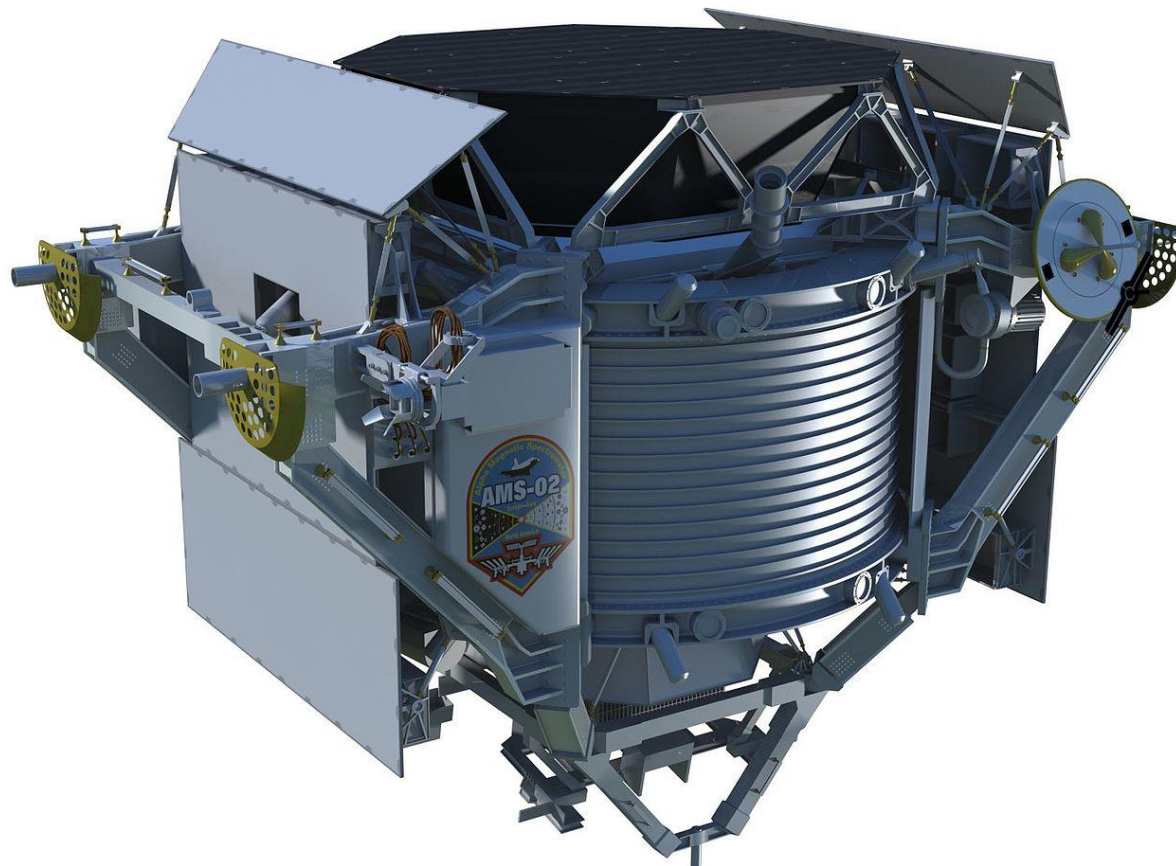
David Miller at MIT has worked on formation flying concepts (see the SPHERES system to the left on the ISS) and on in-space deployment (magnetically enabled structures). Both of these were initiated with NIAC funding and were presented as superconducting systems.



Other  
applications

# Cryogenic Selective Surfaces

Science Mission Support



The alpha magnetic spectrometer on the ISS was originally designed with a superconducting magnet which was replaced with a permanent magnet.

## Other applications

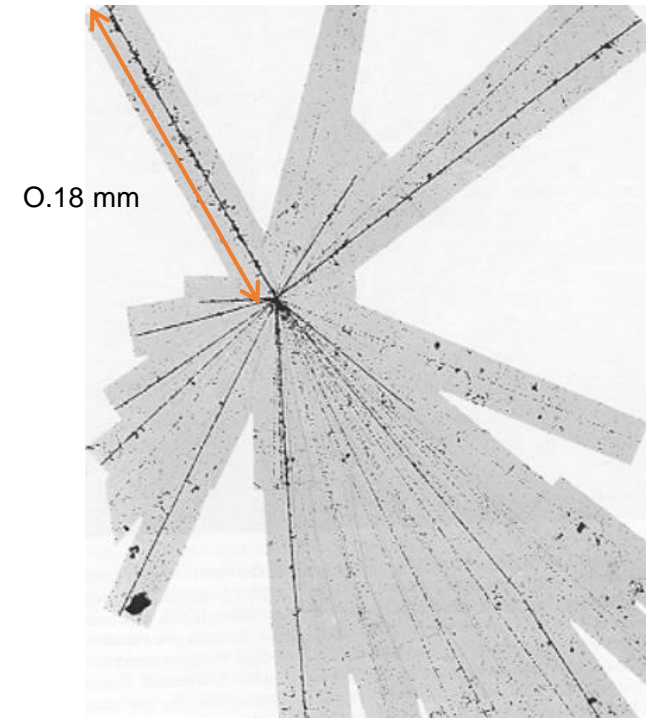
# Cryogenic Selective Surfaces

## Radiation Shielding

But one of the biggest potential applications of superconductors in space is shielding from galactic cosmic radiation (GCR).

At present we cannot go to Mars due to the significant health risk involved from GCR. (National Academies).

And we cannot shield astronauts using material shielding. (ref. Youngquist, et. al., "Thick Galactic Cosmic Radiation Shielding Using Atmospheric Data", Acta Astronautica, 94 (2014). Pp. 132-138).



Galactic Cosmic Ray nuclear collisions as recorded in nuclear emulsions, (Magnesium nuclei)

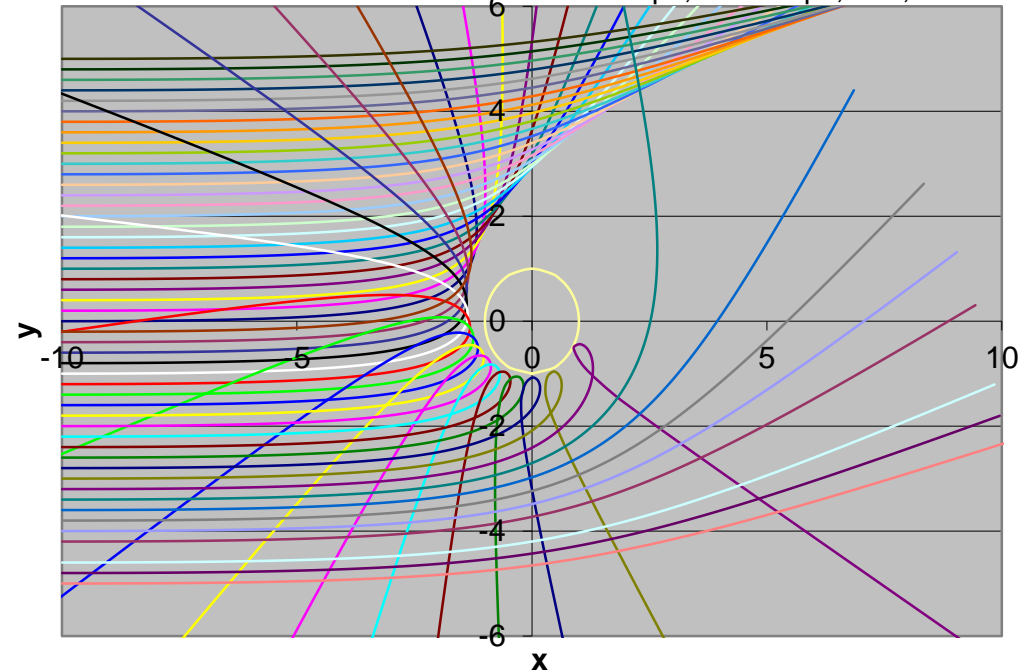
# Cryogenic Selective Surfaces

Ideally, if a magnetic field could be extended out to many kilometers it would not need to be strong. The idea is to emulate the performance of the earth's magnetic field.

This idea was studied in the 1990's but was limited by the lack of a cooling system for the cables.

My submission of the Phase 1 NIAC on Cryogenic Selective Surfaces was originally meant to find a way to cool superconducting cable so that this field could be restarted.

**Solar Proton Trajectories** 1 m radius mag dipole, 200 loops, 200 Amps, 300,000

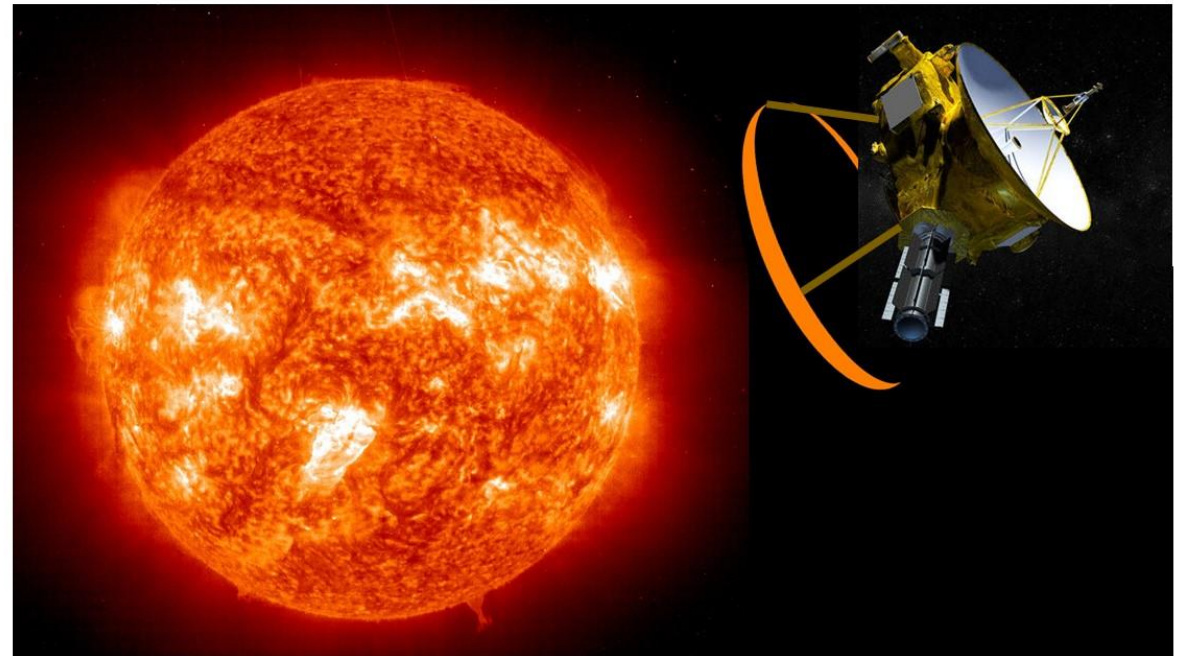


# Cryogenic Selective Surfaces

## Solar Reflectors

If the direction to the Sun is fixed then the new surface can be used as a solar shield, providing (theoretically) as much as 60 times better reflectivity of solar power than the current state-of-the-art.

This may allow future probes to nearly reach the surface of the Sun, an idea recently proposed to NIAC and awarded (2017 Phase 1).





# Cryogenic Selective Surfaces

## Solar White Selective Surfaces—Potential Uses

### Superconductor Operation

If we can reach 40-50 K, then superconductors with a 90K critical temperature can be used for magnetic energy storage.

We could use superconductors for power delivery or to generate magnetic fields over large distances.

A large scale, but relatively weak, magnetic field can provide GCR radiation protection.

### Cryogenics

LOX and LN2 storage on long duration space flights, in space depots, or on the Moon.

### Solar Shielding

A new generation of solar radiation shields could be developed.

# Cryogenic Selective Surfaces



## **Accomplishments Summary for first year of our Phase 2 NIAC Project:**

We have developed a new concept that should allow cryogenic temperatures to be achieved passively in deep space.

We have fabricated rigid versions of the new surface and have shown nearly 100 times better ultraviolet reflection at 375 nm than for silver, the next best option.

We have filed a provisional patent on this novel concept, published it in “Optics Letters”, and submitted a manuscript to the AIAA. We have passed peer-review.

We have obtained co-funding from KSC Internal Research, the Launch Services Program, and STMD Game Changing.

We have made substantial progress in modeling both experiments and mission scenarios and have succeeded in using Thermal Desktop to model our coating (GRC).

# Cryogenic Selective Surfaces



## Plans for remainder of Phase 2 NIAC:

July 2017-July 2018

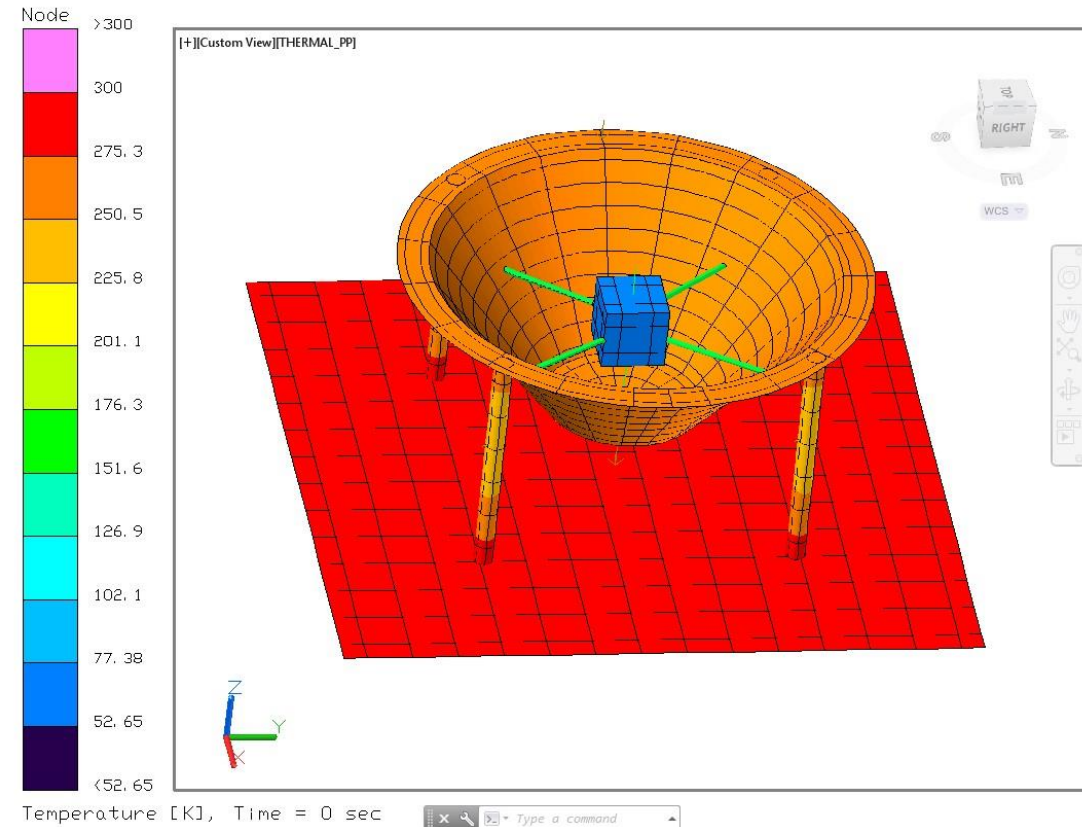
1. Continue to develop the rigid coating-improve fabrication, determine mechanical properties, adhesion to metal surface, test performance, will it survive launch?
2. Test our new coatings in higher fidelity deep space chambers. (We will be developing a small scale chamber here at KSC and W. Johnson will be constructing a larger scale chamber at GRC with Game Changing funds).
3. Continue to study mission architectures. Concentrate on GRC recommended missions (GRC will support with thermal desktop analysis) and on LSP areas of need.

Possible break point.

We have started to design a test configuration that could be placed in low-earth orbit.

A sample would be suspended in a highly reflecting (low emissivity) cone. The cone acts as an IR shield to block IR from the electronics module and the Earth.

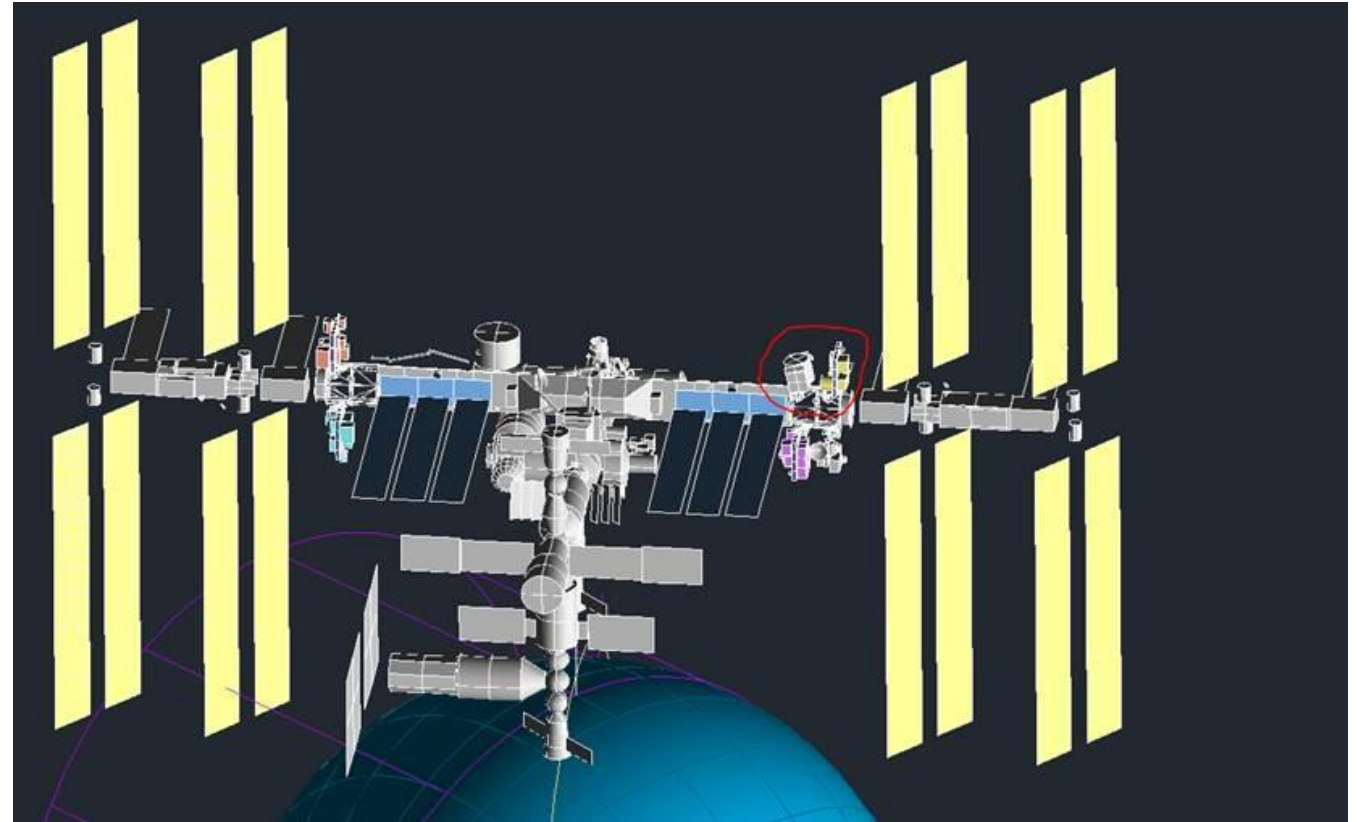
Analysis shows that even in full sunlight the sample should maintain cryogenic temperatures. This important prediction needs to be verified in-flight.



Thermal desktop model of a possible low-earth orbit cryogenic selective surface test.



We considered MISSE as an “easy” route to test our coating, but discovered that the solar panels (which can reach 150 C) would be in our field of view.



The ISS showing the location of MISSE (the Materials ISS Experiment).

Now we are considering a Cube Sat approach.

We may team with a university and propose to the small SAT program.

Prof. Mason Peck at Cornell has asked to work with us on this.



A 1U CubeSat with onboard computer.

**Beyond NIAC**

**Game Changing**

# Cryogenic Selective Surfaces



Molly Anderson is the Principal Technologist for Thermal Management.

She submitted Cryo-Thermal as a need on the MASTER Quantifiable Capabilities Quad Chart (Dec. 2016) list.

She states:

*“Current state-of-the-art is to accept losses or try to adapt relatively low scale cryo-coolers.*

*Zero Boil-off capability is needed to allow long term storage of cryogens. This will enable SLS missions, will enable refueling, will minimize propellant losses, and will enable ISRU liquefaction, transfer, and storage.”*

We are working with Molly to advance and advertise our cryogenic selective surface concept. We believe our new concept may enable Zero Boil off of LOX, Liquid methane, LN2, and Xenon.

**Beyond NIAC**

**Game Changing**

## Cryogenic Selective Surfaces



Molly Anderson is supporting a Game Changing “Seedling” request for FY18. She stated

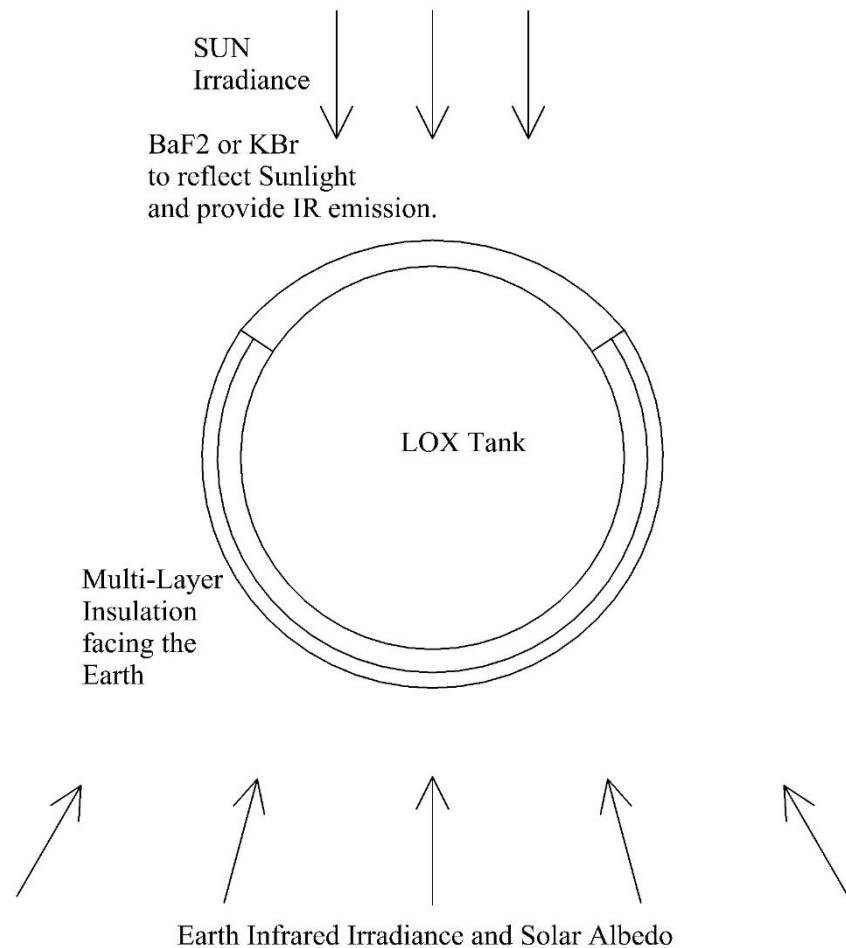
*“I think that one of the things that KSC should do with your unique coating is compare its application and impact in a mission to the other thermal control methods proposed. Thus if you have sufficient FTE for the development, it would be really good to spend some FTE on that kind of analysis.”*

So we plan in FY18 to support this comparison of techniques to allow for long term storage of cryogenics in space.

Wesley Johnson will be overseeing this work.

Game Changing is also funding the deep space simulator development at Glenn.





LSP wants to maintain LOX in low-earth orbit for a long time period (many days). Our new coating can minimize the solar heat load, but it cannot reflect the IR emitted by the Earth.

We are considering a LOX tank with an IR shield composed of a Teflon/silver radiator on the Earth side of the tank and our new coating on the upper side.

# Cryogenic Selective Surfaces



We have contacted Mike Seablom and Dan Moses of SMD. They have asked for updates on the technology and requested that a brown bag presentation be given next year at NASA Headquarters.

## Questions Posed:

1. Can we use our new coating to store LOX on Mars?

It might help by allowing CO<sub>2</sub> to freeze on a LOX tank at night and then the CO<sub>2</sub> frost might act as a solar scatterer/insulator during the day. Atmospheric effects will limit the performance.

2. Can we store liquid Hydrogen (20 K)? (roughly 9 milliWatts/m<sup>2</sup> emitted power!)

If we use our new coating as a Solar shield at 1 AU from the Sun, the shield will drop into the 65K range, assuming a silver backing. The emitted power towards an LH<sub>2</sub> tank would then be about 10 milliWatts/m<sup>2</sup> so there might be a way, but only in deep space without other IR emitters. This may be needed for the nuclear thermal propulsion program.

# Cryogenic Selective Surfaces



## Financial History:

NIAC Phase 1, June 2015 to February 2016

Initial concept development

\$100K

LSP February 2016 – September 2016 (plus some KSC FTE)

First deep space simulation verification with UV rad.

\$ 50K

KSC Internal research funds May 2016 to June 2017

Development of rigid coatings

\$100K

NIAC Phase 2, July 2016 to July 2018

General advancement on all fronts, esp. mission analysis

\$500K

Game Changing seedling project Oct. 2016-Sept. 2017

FTE for NASA, begin to support transition to higher TRL

0.5 FTE

LSP March 2017-September 2017

Low Earth Orbit LOX storage

\$ 50K

Game Changing seedling Oct. 2017-Sept. 2018 (proposed)

Deep space simulator at GRC, publicize the concept,  
look to the future

1.5FTE (KSC)

0.4 FTE+\$80K (GRC)



# Cryogenic Selective Surfaces



## NIAC Finances:

NIAC Phase 2, July 2016 to July 2018	\$499,600
--------------------------------------	-----------

July 2016-Sept. 2016 (FY2016)    all funds used	\$ 63,700.
---	------------

    \$25K to contractor work at KSC

    remaining funds to FTE at KSC, GRC, and AMES

Oct. 2016-Sept. 2017 (FY2017)	\$252,500
-------------------------------	-----------

    \$97K to contractor work at KSC—obligated

    \$27K returned from AMES (S. Johnson retired)-obligated to KSC contractor

    \$5K procurement (powders, new cryo vacuum shroud)

    remaining funds to FTE at KSC and GRC.

Oct. 2017-July 2018 (FY2018)	\$183,400
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    \$71K to contractor work at KSC

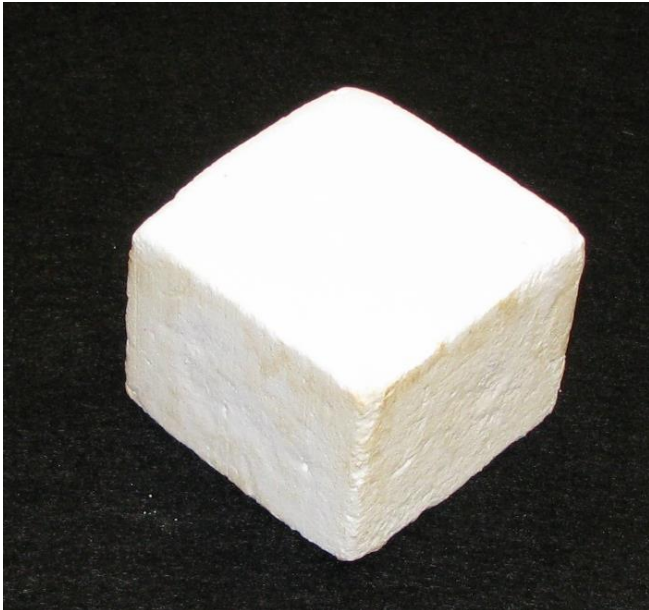
    \$1.5 K procurement for page charges

    remaining funds to FTE at KSC and GRC.

# Cryogenic Selective Surfaces

That's all!

Questions? Open Discussion



A small piece of Shuttle tile material (composed of nearly pure glass fibers), illuminated by flashlights.

